POINTS Science

Introduction

Three sources contributed significantly to this section: the POINTS A.J. paper,"[1] the Astrometric Interferometry Mission Strawman Science Program, and the Open and Globular Clusters report from K. Cudworth of Yerkes Observatory. We include these documents as sections 2-4 in the Appendix.

POINTS measures positions of widely separated objects unresolved by its 2 m baseline (~0.24 μrad = 50 mas at λ = 0.4 μm). Due to its extremely low systematic error, POINTS has extensive potential for realizing fundamental goals in many areas of astrophysics. POINTS can observe field stars, binaries, the brighter black hole candidates, open and globular cluster stars, the brighter stars in nearby dwarf spheroidal galaxies, several AGN, and certain types of solar system objects. Associated with each of these target types is one or more categories of interesting science, as detailed below.

Table 1 introduces the science classes and their relationships to the target categories. The first column serves as a key to both Table 2 and the following text. Table 2 summarizes the target categories, their associated science, and some of their observational properties. The "Science Class" column indicates relevant area(s) of science to which each target class contributes.

The faint magnitude limit of 18 adopted here assumes a slit in the spectrometer, which blocks sky background. If astrophysical science objectives are not considered in hardware design choices, then a slit will not be included and the faint star limit drops to ~14. Table 3 shows the approximate number of available objects at these two magnitudes for the target categories of Table 2. Although some science would be lost, substantial impact would still be made in most areas discussed in this section.

A. Serendipity

Historically, despite our best efforts at predicting and quantifying scientific advances, we often fail to predict the most exciting discoveries that arise from a new observing capability. We expect that unanticipated yet significant discoveries will result from a successful mission.

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[1] Reasenberg, R.D., et al., 1988, Astron J 96, 1731, "Microarcsecond Optical Astrometry: An Instrument and its Astrophysical Applications"

Table 1
Science Classes

Science Class		Primary Target Category
A	Serendipity	-
B	Extragalactic distance scale	Cepheids
C	Mass of the Galaxy	halo objects, LMC
D	Galactic structure	OB stars
	Star cluster dynamics:	
E	galactic	OB stars
F	globular	subdwarfs
G	Stellar masses	binaries
H	Stellar luminosities	O - M stars
I	Evolution of interacting binary systems	nova-like vars
J	Selected exotic objects	black hole candidates
K	Solar system studies	asteroids, satellites
L	Extrasolar planetary system detection and characterization	F, G and K stars
M	Global reference frame	grid objects

B. Extragalactic Distance Scale

Calibration of the extragalactic distance scale is arguably the most important problem in observational cosmology. One of the primary goals of the Hubble Space Telescope (HST) is to determine the Hubble constant to within 10%.[2] Recent determinations differ by 50-100%. Cepheid variables are high-mass, helium core-burning, F to K supergiants (hence intrinsically bright) which are unstable to radial pulsations. The period-luminosity-color (PLC) relation of the Cepheid variables is the cornerstone of extragalactic distance scale.[3] Unfortunately, no Cepheid trigonometric parallax is known. We must use indirect methods to determine their distances. Currently, realistic distance uncertainties are ~10%.[4] Since galactic calibrations are the basis for most extragalactic distance scales and the determination of the Hubble constant, a major weak point is the uncertainty of the distance scale in our Galaxy[5]. Another problem is that interstellar reddening is significant for all galactic Cepheids. POINTS can measure direct distances to Cepheids, thus greatly improving the calibration of the Cepheid absolute luminosities and the PLC relation.

The current level of agreement among extragalactic distance determinations is ~±10% out to ~5 Mpc, and roughly 25% for distances out to the Virgo cluster (~17 Mpc).[6] Distances determined by HST using the Cepheid P-L relation are based on an assumed distance to the LMC. Systematic errors due primarily to the reddening correction and to the adopted LMC distance dominate the resulting ~10% uncertainty in the true distance. A Key Project for the HST is to undertake main sequence fitting on LMC clusters to constrain the Cepheid P-L relation. POINTS can go much further than this by directly determining parallaxes for both galactic and LMC Cepheids.

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[2] Freedman, W.L., et al., 1994, Nature 371, 757, "Distance to the Virgo Cluster Galaxy M100 from Hubble Space Telescope Observations of Cepheids";
Rubin, V., et al., 1985, "Report of the Space Telescope Working Group on Galaxies and Clusters"
[3] See e.g. Feast, M.W., and Walker, A.R., 1987, Ann Rev Astron Astrophys 25, 345, "Cepheids as Distance Indicators"; and Rowan-Robinson, M., 1985, *The Cosmological Distance Ladder*, W.H. Freeman, New York
[4] Hindsley, R.B., and Bell, R.A., 1988, Astrophys J
[5] Reid, M.J., 1993, Ann Rev Astron Astrophys 31, 345, "The Distance to the Center of the Galaxy"
[6] Freedman et al. 1994

Table 2

Science Target Categories

Target Category	Science Class[1]	Magnitude Range	Distance Range	N_S[2]	N_{TOT}[3]	Required Accuracy[4]
Field Stars						
Cepheid Variables	B, H	2.1-17.3	0.4-20 kpc	~30	459	1-5
W Virginis	B, H	8.8-17.7			172	
RR Lyrae Variables	B, D, H	7.7-14.0	7-13 kpc	20-90	6,047	<10
Subdwarfs	E	4.2-13.6	~10-300 pc	<90	>878	<10
O Stars	L, D, H	1.9-15.2	~1-15 kpc		664	~10
F - K Stars	L, H	~0-14		~1000	>80,000	
Planetary Nebulae	B, H	6.8-18			247[5]	
Halo K Giants	C, H	13.2-16.0	1.6-25	20	>106	2-50
Carbon Stars	C	4.5-18			>3066	2-50
Radio Stars	M	1.3-12.6		~30	180	
Interacting Binaries[6]						
Novae	G, H, I	11.3-18			133	
Nova-like Variables	G, I	10-18	~80-250 pc	30-300	408	3
Cataclysmics		14.2-16.6			4	
UX UMa Stars		10-17			10	
Dwarf Novae		10.5-18			233	
AM Her Stars		15.5-18			9	
Symbiotic Stars		3.5-17.6			42	
Be Star Binaries	I	10-15	~3 kpc	2-10	>61	3
WR Stars	G, I, J	1.7-17.7			158	
Globular Cluster Binaries	I	15-18		~5-25		3
LMXRBs	I, J	13-18	0.7-10 kpc	5-25	13	1-3
Black Hole Candidates	I, J	9-18	~3 kpc	4-40	~10	10
Open Clusters	D, F	3-18	48 pc-10 kpc		1,155	< 5-100
Globular Clusters	D, E	~10-15	1.9-18.4 kpc	~15[7]	125[8]	1-10
Dwarf Spheroidals	C	>17	69-78 kpc	1-3	3	
Magellanic Clouds	B, C	>11	~55 kpc			
AGN						
Quasars	M, J	12.2-18			1,959	
BL Lac Objects	J	12.5-18			98	
Solar System						
Asteroids	K				2,914	
Satellites	K				15	

[1] corresponding to column 1 of Table 1
[2] approximate number of objects required for significant scientific impact
[3] approximate total number of objects available to POINTS
[4] approximate accuracy(μas or μas/yr) for useful science on various associated problems
[5] number of PN with central star brighter than m_V = 18.0
[6] at minimum light
[7] containing a total of ~90 cluster subdwarfs
[8] number of globulars with V(HB) < 20.0 and thus numerous stars with V < 18

RR Lyrae variables provide one of the important consistency checks on the galactic distance scale. Yet there is conflict between the distances inferred from Cepheid absolute magnitudes, RR Lyrae absolute magnitudes,[7] and the dependence of RR Lyrae magnitudes on metallicity. RR Lyrae absolute magnitudes as a function of metallicity are critical to determining the ages of globular clusters, which in turn constrain the Hubble constant.

POINTS can measure trigonometric distances to better than 1% to all 28 of the calibrating galactic Cepheids[8] (m < 12) and to many additional ones. This represents an order of magnitude increase in accuracy and an enlargement of the calibration class. POINTS can also test for metallicity effects, both in Cepheids and in RR Lyrae variables. Other distance indicators for which POINTS can make direct distance determinations include O stars[9] and planetary nebulae.[10] There is currently no high-accuracy global reference frame to which HST can tie its observations. However, since HST can observe Cepheids and RR Lyrae variables in all Local Group galaxies, it can provide a direct link to the local galactic distance scale determined by POINTS. Thus, POINTS will greatly improve the most crucial bottom rung of the distance ladder that provides our link to knowledge of the size and age scales of the Universe.

C. Mass of the Galaxy

The total mass of the Galaxy, and the mass distributions within the several components that make up our Galaxy, are ill-determined. Four important parameters are R_0, the distance to the center of the Galaxy, Θ_0, the rotation speed of the local standard of rest around the center of the Galaxy, and the Oort constants, A (a measure of the local shear) and B (the local vorticity), both quantities being mainly due to differential galactic rotation. The Oort constants may be determined from measurements of radial velocity, transverse velocity, and distance for nearby stars. We have

$$\begin{aligned} v_r &= A \cdot r \cdot \sin 2\lambda \\ \mu &= A \cdot \cos 2\lambda + B \end{aligned} \qquad (1)$$

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[7] currently uncertain at a level ~0.2 mag (Barnes, T.G., and Hawley, S.L., 1987, Astrophys J Lett 307, L9)
[8] Feast and Walker, 1987
[9] Garmany, C.D., and Stencel, R.E., 1992, Astron & Astrophys Supp 94, 211, "galactic OB Associations in the Norhtern Milky Way Galaxy. I - Longitudes 55 deg to 150 deg"
[10] Jacoby, G.H., Ciardullo, R., and Ford, H.C., 1988, in *The Extragalactic Distance Scale*, Proceedings of the ASP 100th Anniversary Symposium, ASP, p. 42, "Planetary Nebulae as Distance Indicators";
Jacoby, G.H., Branch, D., Ciardullo, R., Davies, R.L., Harris, W.E., Pierce, M.J., Pritchet, C.J., Tonry, J.L., and Welch, D.L., 1992, PASP 104, 599, "A Critical Review of Selected Techniques for Measuring Extragalactic Distances";
Hui, X., Ford, H.C., Ciardullo, R., and Jacoby, G.H., 1993, Astrophys J 414, 463, "The Planetary Nebula System and Dynamics of NGC 5128. I. Planetary Nebulae as Standard Candles";
Jacoby, 1989, Astrophys J 339, 39;
Kaler, J.B., 1985, Ann Rev Astron Astrophys 23, 89, "Planetary Nebulae and their Central Stars"

Table 3
Number of Objects Brighter than 14th and 18th Magnitude

Target Category	m ≤ 14.0	m ≤ 18.0
Field Stars		
Cepheid Variables	369	459
W Virginis Variables	81	172
RR Lyrae Variables	738	6,047
Subdwarfs	>878	>878
O Stars	656	664
F - K Stars	>80,000	>80,000
Planetary Nebulae	56	247
Halo K Giants	27	>106
Carbon Stars	>2263	>3066
Radio Stars	180	180
Interacting Binaries[1]		
Novae	22	133
Nova-like Variables	59	450
Cataclysmics	0	4
UX UMa	4	10
Dwarf Novae	9	233
AM Her Stars	0	9
Symbiotic Stars	21	42
Be Star Binaries	61	61
WR Stars	131	158
Globular Cluster Binaries		
LMXRBs	1	13
Black Hole Candidates	~6	~10
Open Clusters	1,003	1,155
Globular Clusters[2]	38	125
Dwarf Spheroidals	0	3
Magellanic Clouds		
AGN		
Quasars	13	1,959
BL Lac objects	7	98
Solar System		
Asteroids	464	2,914
Satellites	4	14

[1] at minimum light
[2] Numbers for globulars reflect V magnitudes of the horizontal branch brighter than or equal to 16.0 and 20.0.

in suitable units, where r is the distance to a nearby star, v_r is the star's radial velocity, λ is its galactic longitude, and μ is its proper motion (i.e., transverse velocity). POINTS can accurately measure r and μ to many nearby stars of all spectral types. Thus, when combined with existing radial velocity data, A and B can be accurately determined. This in turn places constraints on Θ_0, R_0, and the local slope of the rotation speed $[d\Theta/dR]_{R_0}$ via the definitions of A and B,

$$A \equiv \frac{1}{2}\left[\frac{\Theta}{R} - \frac{d\Theta}{dR}\right]_{R_0}$$
$$B \equiv -\frac{1}{2}\left[\frac{\Theta}{R} + \frac{d\Theta}{dR}\right]_{R_0} \quad (2)$$

and hence sets the distance scale for the Galaxy. (The next section discusses other methods for determining R_0.)

The rotation curve, $\Theta(R)$, measures the mass distribution. The most reliable method for determining $\Theta(R)$ has been H I velocity measurements, the so-called tangent method. Inside the solar circle, the maximum radial velocity of any material in the disk is

$$v_{\max} = \Theta(R_0 \sin\lambda) - \Theta_0 \sin\lambda \quad (3)$$

Unfortunately, this method fails outside the solar circle. Indirect methods must be used. Current data suggest that the curve is consistent with being flat, or perhaps rising slightly, out to ~18 kpc.[11] However, the errors in velocity and distance are large (>10%), and, more importantly, the shape of the rotation curve from these methods is sensitive to the values *assumed* for Θ_0 and R_0.[12] POINTS

[11]Fich, M. and Tremaine, S., 1991, Ann Rev Astron Astrophys 29, 409, "The Mass of the Galaxy"
[12]Fich and Tremaine 1991;
Fich, M., Blitz, L., and Stark, A.A., 1989, Astrophys J 342, 272

would be able to accurately determine A and B, and hence Θ_0 and R_0, by observing solar neighborhood stars. It could also measure directly the distances and proper motions of bright objects throughout the Galaxy to determine the rotation curve $\Theta(R)$.

The local escape speed may be used to estimate the local mass density. If we assume all nearby stars are bound to the Galaxy,[13] then the escape speed must be greater than the largest observed velocity. Current estimates of the cutoff velocity range from 450 to 650 km/sec.[14] The most serious uncertainty in this method is velocity error, resulting from proper motion and distance uncertainties. (These stars are > 300 pc distant, making ground-based parallaxes inadequate.) POINTS would measure proper motions of and distances to a representative selection (~1000) of solar neighborhood stars with greatly improved accuracy. This will sharpen the cutoff velocity measurement and help discriminate between the various theoretical mass models, including the distribution of the dark matter component.[15]

Another way to probe the galactic potential is to observe the distances and proper motions of halo stars and of the globular clusters and derive their galactic orbits. More than half (84 of 149) of the globular clusters in our Galaxy lie in the range 2-10 kpc from the Sun.[16] At 10 kpc, POINTS could make distance determinations accurate to better than 10% from a few observations, better than 1% from an extensive set, and transverse velocities could be determined to within ±0.2 km/sec. Hence, the orbits of many globular clusters could be determined. This has implications for the formation history and the mass distribution of the Galaxy and would help constrain the various local and global models of the cluster system dynamics. The unknown value of the velocity dispersion anisotropy parameter $\beta(r) \equiv 1 - \overline{v_t^2}/\overline{v_r^2}$, where $\overline{v_t^2}(r)$ is the mean square tangential velocity and $\overline{v_r^2}(r)$ is the mean square radial velocity, plagues attempts to constrain the mass distribution from globular cluster kinematics. β could be determined if accurate distances were available. Distance errors act to erroneously isotropize the dispersion tensor, and observations of tangential velocities do not even exist for the more distant clusters.[17]

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[13] Within limits, this appears to be a safe assumption. Two contaminating populations are Local Group interlopers (Dawson, P.C., and de Robertis, M.M., 1988, in *The Mass of the Galaxy*, ed. M. Fich, p. 21, Toronto: Can. Inst. Theoret. Astrophys.) and escaping stars (Leonard, P.J.T., and Duncan, M.J., 1990, Astron J 99, 608; and Hills, J.G., 1988, Nature 331, 687). However, a spatially uniform population of interlopers of the required density would be inconsistent with local star counts (Leonard, P.J.T., and Tremaine, S., 1990, Astrophys J 353, 486). For escapers, in order for even one to be within a survey radius of, say, 200 pc, ~10^8 such stars must have been ejected over the lifetime of the Galaxy. Such an ejection rate is improbable (Fich and Tremaine 1991). Thus, the assumption that nearby stars are bound to the Galaxy is relatively sound.

[14] Leonard and Tremaine 1990

[15] The density of dark matter alone in the disk appears to exceed the density of visible matter by ~5-50% (Oort, J. 1932, Bull. Astron. Inst. Neth. 6, 249; Bahcall 1984a,b,c), though this is still a matter of dispute (see Carr, B., 1994, Ann Rev Astron Astrophys 32, 531, "Baryonic Dark Matter" for a summary).

[16] e.g. Lang, K.R., 1992, *Astrophysical Data: Planets and Stars*, Springer-Verlag, New York; Ruprecht, J., Balazs, B., and White, R. E. 1981, "Catalogue of Star Clusters and Associations. II. Globular Clusters"

[17] Fich and Tremaine 1991

Stellar halo tracers include K giants, blue horizontal branch stars, carbon stars,[18] and RR Lyrae variables.[19] The halo stars have a large vertical velocity dispersion, about 90 km/s at 6 kpc. This seems to drop off at larger distances: ~60 km/s at 25 kpc from the plane. POINTS could measure all three components of the halo tracer velocity dispersions, as well as determine the bulge rotation rate.[20] Thus, we could make significant progress in discriminating between two possible causes of the drop-off: 1) a change in the orbital structure of the Galaxy, with implications for the separability of the potential and a third integral of the motion; and 2) a true decrease in the mass density of the halo. This second possibility would imply both a truncation and a substantial flattening of the dark matter distribution. Measurements of the proper motions, to an accuracy of 5 km/s = 40 μas, and distances, to a parallax accuracy of 5 % = 2 μas, of, say, ~50 K giants farther than 10 kpc from the disk would suffice to make this distinction. Such stars are readily observable: $m_V \le 16$. In addition, we could make use of parallaxes to calibrate nearer stars and determine spectroscopic parallaxes for the farther stars, which would then reduce the needed parallax accuracy to 10 μas. Additionally, an understanding of the orbital structure of the halo stars will provide clues to the formation of the Galaxy and thereby indirectly improve our understanding of its mass structure.

The volume density of the disk has recently been estimated by Bahcall[21] and by Kuijken and Gilmore.[22] These two groups differ in their estimation of the dark matter component of the disk. A substantial amount of disk dark matter implies a dissipational character, which would rule out most non-baryonic candidates and many baryonic ones. The local volume density can be written in the form

$$\rho = -\frac{1}{4\pi G}\left[\frac{\partial K_z}{\partial z} + 2\,(A^2 - B^2)\right] \tag{4}$$

where A and B are the Oort constants and K_z is the vertical component of the galactic gravitational field. The disk surface density is then

$$\Sigma(z) = \int_{-|z|}^{|z|} \rho(z)\,dz = \frac{1}{2\pi G}|K_z| - \frac{1}{\pi G}(A^2 - B^2)\,|z| \tag{5}$$

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[18]Bothun, G., Elias, J.H., and MacAlpine, G., 1991, Astron J 101, 2220, "Carbon Stars at High galactic Latitude"; Jura, M., Joyce, R.R., and Kleinmann, S.G., 1989, Astrophys J 336, 924, "High-Luminosity Carbon Stars in the galactic Anticenter"

[19]Gilmore, G., Wyse, R.F.G., and Kuijken, K., 1989, Ann Rev Astron Astrophys 27, 555, "Kinematics, Chemistry, and Structure of the Galaxy"; Fich and Tremaine 1991

[20]Minniti, D., White, S.D.M., Olszewski, E.W., and Hill, J.M., 1992, Astrophys J Lett 393, L47, "Rotation of the galactic Bulge"

[21]Bahcall, J.N., 1984 Astrophys J 276, 156; 276, 169; 287, 926

[22]MNRAS 239, Aug. 1, 1989, p. 571-603, 605-649, 651-664, "The mass distribution in the galactic disc. I - A technique to determine the integral surface mass density of the disc near the Sun. II - Determination of the surface mass density of the galactic disc near the Sun. III - The local volume mass density"

Since K_z is proportional to the derivative of the stellar space density distribution, the determination of the local volume mass density depends on the square of the distance scale, and determinations of the surface mass density are linearly proportional to the distance scale.[23] Hence, accurate determination of the galactic distance scale is crucial for understanding the local mass structure of the Galaxy. Gilmore et al. (1989) conclude that systematic errors limit the local volume mass density determinations (the Oort limit). The distribution of K giants perpendicular to the disk is a major source of uncertainty. To resolve this, we would need ~20 parallax measurements of bright K giants (m_V = 10), with individual accuracy 50 µas = 5% error at 1 kpc. This falls well within POINTS capabilities. We would also need space velocities to rule out the existence of separate kinematic subgroups: ~100 K giants to a level of several hundred µas, again well within the range of POINTS.

If we assume the Magellanic Clouds are bound to the Galaxy, measuring their proper motion would provide another constraint on the total mass of the Galaxy, as well as a measure of the dark matter component.[24] Proper motion measurements of the Magellanic Clouds would also greatly improve galactic mass distribution determinations resulting from observations of the Magellanic Stream.[25] The brighter LMC stars are m = 11, and the expected orbital motion is large: ~15 mas/yr (assuming no dark matter).[26] Because POINTS measurements would be in a reference frame tied to the quasars, the systematic errors that beset ground measurements of LMC and SMC motions would be absent. Besides the LMC and SMC, at least seven other satellite galaxies orbit the Milky Way within 300 kpc.[27] Determination of proper motions and distances to these objects would corroborate and extend the Magellanic Cloud measurements.

D. Galactic Structure

Spiral Arm Structure

Are spiral arms due to traveling density waves or to propagating star formation? This is one of the fundamental questions regarding galactic spiral arms. POINTS will be able to differentiate between the two hypotheses by measuring the kinematics of stars near a spiral arm. Density waves will affect stellar motions in a characteristic way; expected peculiar motions are on the order ~20 km/s. Measurements of ~20-50 early-type stars ($m_V \leq 13$) within ~200 pc of the nearby Perseus arm (~2 kpc), to an accuracy of 2% = 10 µas in parallax and 1% = 21 µas/yr in proper motion will suffice. Discrimination at this level is well within POINTS capabilities.

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[23] Gilmore et al. 1989
[24] Fich and Tremaine 1991
[25] Murai, T., and Fujimoto, M., 1980, PASJ 32, 581;
Lin, D.N.C., and Lynden-Bell, D., 1982, MNRAS 198, 707
[26] Lin, D.N.C., and Lynden-Bell, D., 1977, MNRAS 181, 59
[27] Zaritsky, D., Olszewski, E.W., Schommer, R.A., Peterson, R.C., and Aaronson, M., 1989, Astrophys J 345, 759

Distance to the Galactic Center

The Sun's distance from the galactic center sets the galactic distance scale. Many different approaches for determining this distance have been tried, with recent (1974-1993) results ranging from 6.2-10.8 kpc. The best estimate appears to be ~8.0±0.5 kpc.[28] The best primary indicator consists of VLBI determinations of water maser proper motions near the center of the Galaxy. Results are fairly unreliable due to large random motions of the masers and the nonuniform distribution of masers around the exciting star. Hence, we look to secondary and indirect methods. POINTS can contribute significantly to the determination of R_0 in several ways.

Accurate distances to the globular clusters would allow three estimates for R_0. First, if we assume the globular cluster system is symmetrically distributed about the galactic center, the density peak of the cluster locations projected along the line joining the Sun and the galactic center (GC) yields R_0.[29] Accuracy currently depends on the horizontal branch absolute magnitude calibration as a function of metallicity, and upon the extinction correction. Neither of these sources of error affects POINTS's direct measurements of the trigonometric parallaxes of the individual clusters. Second, there is reason to believe that the density of globular clusters decreases in a cone (opening angle ~15°) aligned on the galactic rotation axis.[30] Adjusting R_0 to maximize the cone angle yields the GC distance. Accurate globular cluster distances are necessary to characterize this cone of avoidance. Third, the metallicity of globular clusters decreases with distance from the GC. If the cluster distribution is azimuthally symmetric about the galactic rotation axis, then R_0 can be determined by requiring that the metallicity be uncorrelated with galactocentric azimuth. This method has the (ground-based) advantage that metallicity determinations are relatively insensitive to extinction corrections. Again, accurate cluster distances are needed.

RR Lyrae variables can be seen across the Galaxy through low-extinction windows (such as Baade's Window or the one at $l = 0$, $b = -8$ [31]). Similar to the method for globular clusters, the RR Lyrae distribution peak in such windows can be used to estimate R_0.[32] Principal sources of systematic error for this method include the unknown metallicity dependence of the RR Lyrae absolute magnitude calibration, uncertainties in the extinction correction, and the calibration of the RR Lyrae PLC relation.[33] By measuring accurate distances, POINTS can calibrate the

[28]For a review, see Reid, M.J., 1993, Ann. Rev. Astron. Astrophys. 31, 345, "The Distance to the Center of the Galaxy"

[29]e.g. Racine, R., and Harris, W.E., 1989, Astron J 98, 1609, "Globular Clusters and the Distance to the galactic Center"

[30]Wright, A.E., and Innanen, K.A., 1972, BAAS 4, 267;
Sasaki, T., and Ishizawa, T., 1978, Astron & Astrophys 69, 381

[31]Oort, J.H., and Plaut, L. 1975, Astron & Astrophys 41, 71

[32]e.g. Walker, A.R., and Terndrup, D.M. 1991, Astrophys J 378, 119;
Fernley, J.A., Jameson, R.F., Longmore, A.J., Watson, F.G., and Wesselink, T., 1987, MNRAS 226, 927, "The Absolute Magnitude of RR Lyraes and the Distance to the galactic Centre"

[33]Reid 1993

absolute magnitude scale as a function of metallicity, sidestep the extinction correction problem, and calibrate the RR Lyrae PLC relation.

Other bright stars, such as Mira variables, are visible through interstellar windows.[34] These luminous giants currently have an uncertain absolute magnitude calibration, due mainly to the complex molecular opacity sources in their cool atmospheres. Additionally, there is uncertainty regarding the differences between the solar neighborhood (Pop. I) Miras and the galactic center (Pop. II) Miras. POINTS, again through direct distance determinations, can provide the necessary absolute magnitude calibrations for both populations, in addition to another determination of R_0.

Indirect methods for determining R_0 can be useful. One is to adopt a galactic rotation model and combine it with distances of tracers that participate in that rotation. [Combining radial velocities with the kinematic model for the Galaxy to derive kinematic distances, one can solve for R_0 such that the kinematic and luminosity distances agree. Another method is to use Oort's A parameter (i.e., the local velocity shear) to obtain a galactic distance scale: given radial velocities and distances for solar neighborhood stars, one can solve for R_0 so that the observed velocity shear matches that of a model.] Finally, one may use radial velocities and distances of Cepheid variables in a galactic rotation model to determine the galactic distance scale.[35] Most of these indirect methods are sensitive to local deviations from circular motion and to extinction corrections, and some are sensitive to the circular rotation speed of the Sun.

Galactic Rotation Curve Beyond the Solar Circle

The rotation curve inside the solar circle is well-determined, mainly from H I observations.[36] Such is not the case beyond the Sun's orbit. By measuring the distances and proper motions of disk tracers (OB stars) outside the solar circle, POINTS can conclusively determine the rotation curve for the outer Galaxy to ~15 kpc. The necessary observations fall well within the capabilities of POINTS: $m_V \leq 12$, distance accuracy 10% = 10 μas, and proper motion accuracy 10 km/s = 200 μas/yr.

Reddening

POINTS can contribute substantially to the determination of the structure of our Galaxy. Essential to setting the size scale of the Galaxy, in addition to determining absolute luminosities of massive stars in various evolutionary stages, is the relationship between reddening and

[34] Glass, I.S., and Feast, M.W. 1982, MNRAS 198 199, "Infrared Photometry of Mira Variables in the Baade Windows and the Distance to the galactic Centre"
[35] Caldwell, J.A.R., and Coulson, I.M., 1987, Astron J 93, 1090, "Milky Way Rotation and the Distance to the Galactic Center from Cepheid Variables"
[36] Fich and Tremaine 1991; Fich et al. 1989

extinction. Extinction must be taken into account for distances greater than about 100 pc.[37] Over much of the spectrum, A_λ (the number of magnitudes of extinction at wavelength λ) falls sharply with increasing wavelength.[38] In the visual band, we have, approximately,

$$A_V = R \cdot E(B-V) \tag{6}$$

where E(B-V) is the observed color excess and R is a proportionality constant (the ratio of total to selective absorption), R ~ 3.1 ± 0.2.[39] There is some disagreement over the exact form of eq. (6)[40] (that is, how to account for the variation of R with spectral type). Burstein and Heiles[41] provide contour maps of E(B-V). Apparently, the most accurate form of the extinction relation is one due to Fisher and Tully,[42]

$$\left.\begin{aligned}
A_B &= \begin{cases} 0 & N_H \le 232 \\ -0.149 + 6.41 \cdot N_H & N_H > 232 \end{cases} \\
N_H &= \begin{cases} 323 \csc|b| & b < 0 \\ 323 \csc|b| + [105 - 3.8\,b - 89\cos(\lambda - 140)] & b > 0 \end{cases} \\
A_B &= (R+1)\,E(B-V) \\
\text{and} \\
R &= \frac{A_V}{E(B-V)} = \frac{3.1 + 0.3\,(B-V)}{1 - 0.02\,A_B}
\end{aligned}\right\} \tag{7}$$

where b is the galactic latitude, λ is the galactic longitude, and N_H is the neutral hydrogen column density (in units of 10^{18} atoms cm^{-2}). There is some dependence of R on spectral type, due to the finite width of the spectral bands. This is (at least partially) taken into account in eqs. (7). POINTS could measure trigonometric distances directly to massive stars such as OB stars, Wolf-Rayet stars, and Cepheids, sidestepping the uncertainties in the amount of reddening and in the relation between absolute magnitude and spectral type. In addition, we could assess the extinction relation eq. (6) through different paths through the ISM.

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[37] Rowan-Robinson 1985

[38] see, e.g., Savage, B.D., and Mathis, J.S., 1979, Ann Rev Astron Astrophys 17, 73, "Observed Properties of Interstellar Dust"

[39] Mihalas, D., and Binney, J., 1981, *Galactic Astronomy*, W.H. Freeman, San Francisco

[40] Blanco, V.M., 1956, Astrophys J 123, 64, "Some Remarks on the UBV System";
Lee, T.A., 1970, Astrophys J 162, 217, "Photometry of High-Luminosity M-Type Stars";
Humphreys, R.M., 1979, Astrophys J Supp 39, 389, "Studies of Luminous Stars in Nearby Galaxies. II. M Supergiants in the Large Magellanic Cloud";
Morgan, D.H., and Nandy, K., 1982, MNRAS 199, 979, "Infrared Interstellar Extinction in the LMC"

[41] Burstein, D., and Heiles, C., 1982, Astron J 87, 1165, "Reddening Derived from HII and Galaxy Counts: Accuracy and Maps"

[42] Fisher, J.R., and Tully, R.B., 1981, Astrophys J Supp 47, 139, "Neutral Hydrogen Observations of a Large Sample of Galaxies"; see also Rowan-Robinson (1985)

Three-dimensional Distribution of Interstellar Clouds

Bright background starlight passing through intervening interstellar clouds contains interstellar absorption lines. POINTS could determine accurate distances to many of these stars, allowing us to map out more fully and to greater distances the distribution of the cold, warm and hot ISM components.[43]

The Galactic Thick Disk

Modern star counts provide evidence for a galactic "thick disk", composed of metal-poor stars with a vertical scale height on the order ~1-1.5 kpc.[44] POINTS could prove vital in determining the kinematics of the thick-disk population and thus discriminating between the many thick-disk formation models. Measurements would be made of stars ≳2 kpc above the plane, where the thick disk dominates.

The Galactic Warp

The nearest edge-on spiral disk is the Milky Way. Early 21 cm radio observations showed that our galactic disk is warped beyond the solar circle.[45] At R~16 kpc in the north, the H I disk curls up to over 3 kpc above the plane, while in the south the disk extends ~1 kpc below the plane at R~15 kpc and turns back up, reaching the plane again at R~20 kpc.[46] The warp can also be characterized by studies of the distances and proper motions of OB stars in the outer disk.[47] Current optical studies are hampered by uncertainties in the optical reference frame, and it is difficult to explain the warp with existing dynamical models.[48] POINTS observations of the galactic warp would help constrain the models and provide valuable information about the halo mass distribution and the later stages of galaxy formation.

E. Globular Clusters

The globular clusters provide an ideal laboratory for studying stellar evolution and long-term stellar dynamical effects. The relaxation time in the core is ~10^8 yr, while in the outer parts it is

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[43]See e.g. Frisch, P.C., and York, D.G., 1984, IAU Symp. 81, p. 113, *The Local Interstellar Medium*, eds. Kondo et al.

[44]e.g. Gilmore, G., Wyse, R.F.G., and Kuijken, K., 1989, Ann Rev Astron Astrophys 27, 555, "Kinematics, Chemistry, and Structure of the Galaxy"

[45]Burke, B.F., 1957, Astron J 62, 90;
Kerr, F.J., 1957, Astron J 62, 93

[46]Henderson, A.P., Jackson, P.D., and Kerr, F.J., 1982, Astrophys J 263, 116

[47]Miyamoto, M., Yoshizawa, M., and Suzuki, S., 1991, Astrophys. Space Sci. 177, 399, "The galactic Warp and Rotations of the Fundamental System";
Miyamoto, M., Yoshizawa, M., and Suzuki, S., 1988, Astron & Astrophys 194, 107, "An Optical Warp of the Galaxy"

[48]Binney, J., 1992, Ann Rev Astron Astrophys 30, 51, "Warps"

on the order of a Hubble time. Globular clusters represent important probes of the galactic halo potential, their ages place a bound on the age of the universe, their member star absolute luminosities place constraints on stellar evolution models, and they are useful for tracing the development of the formation of the Milky Way.

The evidence that some metal-poor globulars appear to be older than some ages determined for the universe poses an interesting problem. This can be resolved at the globular cluster end in three ways. One of the principle uncertainties in the ages of the globular clusters is determining the main sequence turn-off point which in turn requires accurate calibration of the absolute magnitude of the main sequence. For ages to be accurate to a billion years, cluster parallaxes must be measured to better than 3%. POINTS could do this with a handful of observations for the 22 globular clusters within ~6 kpc of the Sun. A more extensive set of measurements such that σ_π~1 μas increases the limiting distance to 30 kpc, giving access to ~120 clusters.[49] Aside from questions regarding crowded fields (see section III.C), this is within the capabilities of POINTS. Another approach is improved absolute magnitude calibration of field subdwarfs vs. color and metallicity, for fitting globular cluster main sequences. A third and complementary avenue of attack is calibration of absolute magnitudes of bright RR Lyrae variables vs. metallicity and period, fixing the globular cluster horizontal branch. POINTS could accomplish all three tasks handily.

Determination of the proper motions of a representative sample of globular clusters would directly yield the distribution of orbital angular momentum for the globular cluster system, providing information about the galactic potential. It would also determine the orbits of individual clusters, allowing studies of the correlations between metal abundance, perigalactic distance, cluster radius, and orbital eccentricity, with strong consequences for theories of the formation of the Galaxy.

Other problems involving the globular clusters include age differences among the individual clusters, the so-called second parameter problem,[50] and cluster internal dynamics. POINTS astrometry, in combination with radial velocity data, would provide information along all three axes of the velocity dispersion tensor and unequivocally constrain dynamical models. POINTS will be able to make a significant impact in all of these areas. Because of their brightness, we have an almost complete sample of clusters to observe. Because proper motions and positions are with respect to the POINTS GRF, there is no need for nearby zero-proper-motion objects (quasars). Hence, we can observe clusters near the galactic plane. Table 4 summarizes the sci-

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[49] Tello, C., 1994, Astron J 107, 1381, "Sampling of Globular Clusters and the Distance to the galactic Center. I. Data Description and Analysis"

[50] Zinn, R., 1993, in *The Globular Cluster-Galaxy Connection*, ASP Conf. Ser. 48, eds. G. Smith and J.Brodie, p. 38

Table 4 *Star Cluster Science*

Science Class / Problem	m_V[1]	D[2] / σ[3]
Ages & distances of globular clusters	12-15	2-20 kpc
Universe-cluster age discrepancy		distances to 1-2%
Individual cluster age differences		distances to a few percent
Second parameter problem		distances to a few percent
Globular cluster distance scale		distances to 1%
Ages & distances of old open clusters	14-16	< 10 kpc
		parallax to < 5%
Kinematics of globular clusters	14-17	2-50 kpc
		40 μas/yr
Kinematics of old open clusters	14-16	< 10 kpc
		100 μas/yr
Internal dynamics of globular clusters	13-15	< 10 kpc
		20 μas/yr
Internal dynamics of old open clusters	16-17	< 5-10 kpc
		10 μas/yr
Young open clusters	< 12-14	< 2-4 kpc
Stellar luminosity calibrations		distances to 1%
Galactic rotation		50 μas/yr
Internal dynamics		20 μas/yr
Orion nebula		~10 μas/yr

[1] approximate visual magnitude range for significant scientific impact
[2] distance range (top line of each science class)
[3] level of accuracy required for significant scientific impact (current accuracies are ~1 mas and ~mas/yr)

ence that POINTS can address involving the globular clusters (as well as the open clusters, discussed next).

F. Open Clusters

Galactic and Magellanic Cloud open clusters provide another rich source of astrophysically interesting problems. The old open clusters are important for determining galactic disk evolution. Ground-based observations are complicated by the combined effects of age, distance, interstellar reddening, and the lack of "standard candles." The present relatively crude radial velocity data would be enormously improved by accurate proper motions. With POINTS, the distances and ages of old and young open clusters could be determined. The latter would have a substantial impact on the determination of galactic rotation and the structure of the spiral arms. In addition, we should be able to determine the velocity dispersions and dissolution timescales of associations; the open cluster in the Orion nebula is especially interesting. Another exciting possibility is obtaining a fully three-dimensional picture of the nearby open clusters. For the Pleiades (~130 pc), a 5 μas parallax error represents a 0.08 pc distance error, yet the cluster depth is ~4 pc. Similarly, for a proper motion error of 5 μas/yr, the velocity error would be only 3 *meters* per second, yet the internal velocity dispersion is on the order of 0.5 km/s. Young open clusters serve as tracers for star formation, so that accurate distances would prove invaluable for mapping the spiral arms, regions of sequential star formation,[51] and the history of star formation in the Galaxy. Table 4 summarizes some of the many areas of star cluster science for which POINTS

[51] Elmegreen, B.G., and Lada, C.J., 1977, Astrophys J 214, 725

could have a significant impact. Much of this is abstracted from the Appendix, written by K. Cudworth of Yerkes Observatory.

G. Stellar Masses

Stellar masses have been determined mainly for detached main-sequence eclipsing binaries with well-separated spectral lines of the two components, and for nearby visual binaries of known parallax.[52] Less than 5% of visual binaries (most of which are less than 20 pc distant) have good mass determinations.[53] POINTS, with its 3-4 orders of magnitude parallax measurement improvement, would greatly increase the number of accurate mass determinations. Further, since POINTS measurements would give the motions of each component in an inertial frame, the individual masses of both components could be determined, rather than the usual sum of masses.

An intriguing possibility for determining masses for isolated foreground stars is the deflection of light from background stars. The changing impact parameter produced by the relative motion of the stars will lead to an apparent variation in the position of the background star. Lens candidates might be found in catalogs of high-proper-motion stars.[54]

Masses for the most massive stars – O, B, and Wolf-Rayet (WR) stars – would constrain high-mass stellar evolution models, especially the later stages of evolution.[55] POINTS could observe binaries containing high-mass components[56] and determine their masses, as well as calibrate the absolute luminosities of these stars.[57]

H. Stellar Luminosities

One of the most fundamental relations in stellar astrophysics is that among mass, luminosity, chemical composition, effective temperature, and age. Only relatively nearby stars are astrometrically available for determining all of these parameters, so current knowledge spans just a few spectral types. POINTS's distance measurements would increase the useful observing volume a

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[52]Popper, D.M., 1980, Ann Rev Astron Astrophys 18, 115

[53]Heintz, W.D., 1985, in Calibration of Fundamental Stellar Quantities, IAU Symp. 111, eds. Hayes et al., Reidel, p. 71

[54]e.g. Gliese, W., 1969, Veroff. Astron. Rechen-Inst. Heidelberg No. 22;
Gliese, W., and Jahreiss, H., 1979, Astron & Astrophys Supp 38, 423

[55]Abbott, D.C., and Conti, P.S., 1987, Ann Rev Astron Astrophys 25, 113, "Wolf-Rayet Stars"

[56]The binary frequency among O stars and WR stars is ~40-45% (Garmany, C.D., Conti, P.S., and Massey, P., 1980, Astrophys J 242, 1063; Moffat, A.F.J., Lamontagne, R., Shara, M.M., and McAlister, H.A., 1986, Astron J 91, 1392)

[57]Currently, O star and WR star absolute luminosity calibrations rely mainly on distance determinations to galactic clusters containing these objects (Lundstrom, I., and Stenholm, B., 1984, Astron & Astrophys Supp 58, 163). POINTS, by making direct distance measurements to fields stars as well as cluster members, could greatly improve these calibrations. O stars are brighter than m = 15, and most galactic WR stars (129 out of 158) are brighter than m = 14.0.

billion-fold and would permit coverage of all spectral types. By concentrating on binary systems within clusters, we could empirically add age to the mass-luminosity relation and more fully test stellar evolution models.

Among the most luminous stars in our Galaxy are the O stars, the faintest of which is $m_V = 15.2$.[58] As with the Cepheids, none is close enough for ground-based trigonometric parallax measurements. The same problem exists for all early spectral types, from O to A. Hence, the only methods currently available for absolute magnitude calibration of these stars are color-magnitude (CM) diagram fitting and secular and statistical parallaxes. POINTS would measure trigonometric parallaxes for early stars, thereby finally putting their absolute magnitude calibrations on a firm footing.

I. Evolution of Interacting Binary Systems

The evolutionary history of interacting binary systems is a major unsolved problem in astrophysics. These interesting systems include novae, nova-like variables,[59] Be star x-ray binary systems,[60] Wolf-Rayet stars,[61] low-mass x-ray binaries (LMXRBs), Type I supernovae, and galactic black hole candidates (BHCs).[62] The origins of these systems are intimately associated with the complex behavior of compact binaries with mass transfer and mass loss. Questions involving interacting binaries are closely related to stellar mass determination. It is impossible to place any particular system in its evolutionary context without accurate knowledge of the masses and orbital separation. By measuring the motion of the center of light in compact binaries (for which we have radial velocity information for the secondary), POINTS can provide measurements of the orbital inclination and separation. The scarcity of definitive mass and orbit determinations suggests that even a modest number of POINTS measurements will represent a breakthrough.

Specific questions that will be addressed by accurate mass and orbit determinations include: What are the precursors to LMXRBs? Are they formed by accretion-induced collapse of white dwarfs? How many are in hierarchical triples? How does the mass distribution of neutron stars compare with that of high-mass x-ray binaries? What is the origin of Type I supernovae? Are there enough white dwarf binary systems with masses near Chandrasekhar limit to account for SN I numbers? If accretion onto white dwarfs past the Chandrasekhar limit leads to Type I

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[58] Catalogue of galactic O Stars, Cruz-Gonzalez, C., et al. 1974, Rev. Mex. Astron. Astrof. 1, 211
[59] Nova-like variables include cataclysmic variables, UX UMa variables, dwarf novae, AM Her stars, symbiotic stars.
[60] These consist of a recently-formed neutron star and a Be star companion in an eccentric orbit.
[61] Massey, P., 1981, Astrophys J 246, 153;
Moffat, A.F.J., Lamontagne, R., Shara, M.M., and McAlister, H.A., 1986, Astron J 91, 1392;
Vanbeveren, D., and Conti, P.S., 1980, Astron & Astrophys 88, 239
[62] Cowley, A.P., 1992, Ann Rev Astron Astrophys 30, 287, "Evidence for Black Holes in Stellar Binary Systems"

supernovae, millisecond pulsars, or low-mass x-ray binaries, then a significant fraction of accreting white dwarf binaries should have high-mass primaries. If cataclysmic variables are the progenitors, then more than 10% of them should have white dwarfs in the mass range 1.2-1.4 solar masses. What is the distribution of black hole masses? POINTS could furnish definitive black hole masses and the beginnings of a black hole mass distribution. This would provide a critical test for black hole formation models. How is accretion driven? (Secondary evolution? Magnetic braking? Mass loss? Angular momentum loss?) What is the evolutionary state of the secondary in a particular accreting system? POINTS has the potential to provide unique insights into these questions.

J. Selected Exotic Objects

The strongest case for the existence of black holes would be to determine dynamical masses of binary systems containing BHCs. Table 5 contains a list of BHCs, based mainly on a table from Cowley, from which we see that up to nine objects are within potential observing range of POINTS. Included in this list is the exotic SS 433 (~5 kpc, V=14.2).[63]

K. Solar System Studies

POINTS has potential to make significant contributions to our knowledge of the solar system. Current determinations of asteroid masses are as sparse and inaccurate as 20 years ago.[64] The astrometric method, where accurate asteroid positions are determined pre- and post- encounter with another passing asteroid, is the best one for determining single-asteroid masses. The observed perturbations are used to determine the mass of the perturber. POINTS could be used with this technique to determine asteroid masses much more accurately than is currently possible. At $m \leq 14$, there are 464 numbered asteroids when at opposition. For a magnitude cutoff of 18.0, there are 2914 numbered asteroids available. This is far more than could be studied as part of a reasonable observation schedule.[65] In addition, observations of suitably small planetary satellites[66] could be used to determine planetary masses and low-order zonal gravitational harmonic coefficients. Also, the positional accuracies of occultation stars could be greatly improved. Finally, POINTS could place the solar system in the extragalactic reference frame.

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[63] Margon, B., and Anderson, S.F., 1989, Astrophys J 347, 448, "Ten Years of SS 433 Kinematics"; Margon, B., 1984, Ann Rev Astron Astrophys 22, 507, "Observations of SS 433"

[64] Hoffman, M. (1989). "Asteroid Mass Determination: Present Situation and Perspectives", in *Asteroids II*, eds. Binzel, R.P., Gehrels, T., and Matthews, M.S., U. Arizona Press, Tucson

[65] Reasenberg, R.D., 1984, BAAS 16, 758, "Microarcsecond Astrometric Interferometry," arrives at a similar result.

[66] There are 14 with visual magnitude brighter than 18, and 4 brighter than 14.

Table 5 *Black Hole Candidates*

Source	m_V	spec[1]	D (kpc)	M[2]	type[3]	P_{orb} (days)	flick[4]	QPO[5]
LMC X-3	17	B3 V	55	4-11	P	1.7		
V616 Mon	11.26-20.2	K5-7 V	1.0	>3-9	T	0.32		
Cyg X-1	9	B I	2.5	9	P	5.6	•	
LMC X-1	14.5	O7 III	55	4-10	P	4.2		•
CAL 87	19.1-20.9	F/G	55	>4?	P	0.44		
4U0142+61					P	0.02	•	
Nova Mus 1991	13.4-20		1.4		T	0.36/0.43		
4U1543-47	13-15	A V?			T			
4U1630-47	unid.				T		•	
V821 Ara	16.2-21			<2.5?	P	0.62	•	•
V2107 Oph	16.5-21				T			
4U1743-322					T			
V4134 Sgr					P	0.18		
SS 433	~14.2		~5	6-20?	P	13.09		
V1408 Aql					P	0.39		
QZ Vul	18	K V?	1.7-3.2		T	0.34?	•	
V404 Cyg	11.5-18.3	G/K	1-3	8-15?	T	6.45?	•	

[1] spectral type of suspected optical counterpart

[2] suspected mass of massive component, in solar masses

[3] T = transient, P = persistent

[4] rapid flickering observed

[5] quasiperiodic oscillations seen

L. Extrasolar Planetary System Detection and Characterization

POINTS is an ideal instrument for detection, characterization, and classification of planets in stellar systems. Most theoretical studies have concentrated on the formation of our own planetary system; we know very little about how frequently planetary systems can form. Thus, knowledge of the taxonomy of such systems would greatly enhance the understanding of our system and of the formation process. POINTS would address this directly by examining systematically a large number and variety of stars, emphasizing those of solar-type. Sensitivity is such that nondetection of planetary systems would be scientifically significant.[67] If planetary systems are

[67] e.g., Jupiter-size objects orbiting nearby (~10 pc) solar-mass stars will produce an astrometric wobble two orders of magnitude larger than the POINTS single-measurement uncertainty. Rigorous double-blind simulations (Babcock and Reasenberg, TM91-04, "Simulations of Planetary Searches Using POINTS") show that, typically, a

[Continued on next page...]

common, then enough could be studied and characterized to allow meaningful taxonomic classification. POINTS could determine the prevalence and characteristics of planetary systems (masses, orbital elements, and number of planets) as a function of spectral type, and it could address the possible existence of planetary systems in stellar binaries and triples.

M. Global Reference Frame

Of considerable astrophysical importance is the definition of a superbly accurate global reference frame (GRF). This is one of the essential responsibilities of astrometry. Statistical position errors of order 10 milliarcseconds (mas) at the mean epoch ~1940 characterize the current optical frame, defined by the FK5 catalog.[68] Systematic errors exist at the ~0.1-0.2 arcsec level,[69] and error due to proper motion errors accumulates at a rate of about 1 mas/yr. The HIPPARCOS proper motion errors are approximately 2 mas/yr,[70] mainly due to the short mission lifetime. Distortions in the HIPPARCOS GRF are expected to be ~2 mas and cannot be removed by linking with the radio reference frame.[71] Hence, during the epoch of a POINTS mission, the best optical reference frame positions will be accurate at about the ~40 mas level. Currently, the radio reference frame (based on observations of quasars and AGN), accurate to about 1 mas, and the optical frame differ by ~20 mas.[72] Current reference frames are plagued by systematic error and degradation due to proper motion uncertainties.

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[67][Continued from previous page...]
greater than 90 percent detection probability exists for signatures between 0.01 and 0.05 Jove, and 100 percent above 0.05 Jove, with no false detections. One Jove is defined as the astrometric signature of the Sun due to Jupiter as seen from 10 pc.

[68]Fricke, W., Schwan, H., Lederle, T., Bastian, U., Bien, R., Burkhardt, G., Dumont, B., Hering, R., Jaehrling, R., and Jahreiss, H., 1988, *Fifth Fundamental Catalogue (FK5). Part 1: Basic Fundamental Stars*;
Fricke, W., Schwan, H., Corbin, T., Bastian, U., Bien, R., Cole, C., Jackson, E., Jaehrling, R., Jahreiss, H., and Lederle, T., 1988, *Fifth Fundamental Catalogue. Part 2: The FK5 Extension - New Fundamental Stars*

[69]J.F. Chandler, 1994, private communication;
Lindegren, L., Van Leeuwen, F., Petersen, C., Perryman, M.A.C., and Soderhjelm, S., 1992, Astron & Astrophys 258, 134, "Positions and Parallaxes from the Hipparcos Satellite: A First Attempt at a Global Astrometric Solution";
Carrasco, G., and Loyola, P, 1992, Astron & Astrophys Supp 95, 355, "Santiago Fundamental Catalogue - A Catalogue of 1105 FK5 Stars (Equinox J2000.0)";
Morrison, L.V., Gibbs, P., Helmer, L., Fabricius, C., and Einicke, O., 1991, Astrophys. Space Sci. 177, 31, "Evidence of Systematic Errors in FK5"

[70]Kovalevsky, J., 1991, Astrophys. & Space Sci. 177, 457, "Objectives of Ground-Based Astrometry after HIPPARCOS"

[71]Lattanzi, M.G., Bucciarelli, B., and Bernacca, P.L., 1990, Astrophys J Supp 73, 481, "On the Problem of the HIPPARCOS Reference Frame";
see also Kovalevsky, J., 1992, in *ESA, Targets for Space-Based Interferometry*, p. 9, "The Need of very Accurate Optical Astrometry by Interferometric Techniques"

[72]Ma, C., Shaffer, D.B., De Vegt, C., Johnston, K.J., and Russell, J.L., 1990, Astron J 99, 1284, "A Radio Optical Reference Frame. I - Precise Radio Source Positions Determined by Mark III VLBI - Observations from 1979 to 1988 and a Tie to the FK5"

POINTS is by design a global astrometry instrument, capable of constructing a bias-free GRF accurate to a few *micro*arcseconds over the entire celestial sphere. Such a reference frame will be about three orders of magnitude more accurate than the likely best available optical reference frame. From observations of bright quasars and AGN, as well as radio stars,[73] the POINTS GRF will be tied directly to the radio frame. Hence, systematic errors in the radio frame may be found and characterized, and determination of the coincidence between radio and optical emissions will be greatly improved. Further, we can place significant bounds on the proper motions of bright, well-separated quasars, with subsequent cosmological implications.

[73]Walter, H.G., Hering, R., and De Vegt, Ch., 1990, Astron & Astrophys Supp 86, 357, "An Astrometric Catalogue of Radio Stars";
White, G.L., Jauncey, D.L., Harvey, B.R., Savage, A., Gulkis, S., and Preston, R.A., 1991, Astrophys. Space Sci. 177, 79, "Astrometry of Southern Radio Sources";
Xu, T.-Q., Lu, P.-Z., Wang, S.-H., and Chu, Z.-Y., 1991, Chinese Astr. Astrophys. 15, 19, "Optical Positions of Radio Stars and Radio Sources";
Requieme, Y., and Mazurier, J.M., 1991, Astron & Astrophys Supp 89, 311, "Optical Positions of 221 Radio Stars Obtained with the Bordeaux Automatic Meridian Circle";
Lestrade, J.-F., Phillips, R.B., Preston, R.A., and Gabuzda, D.C., 1992, Astron & Astrophys 258, 112, "High-Precision VLBI Astrometry of the Radio-Emitting Star Sigma CrB - A Step in Linking the Hipparcos and Extragalactic Reference Frames"