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OBSS-RV memo, V01
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----------PREAMBLE---

SIM & GAIA will "solve" most outstanding questions in Galactic structure and stellar evolution. That data will also show that neither stars nor the Galaxy are as simple as we currently envision. To make headway in the "beyond SIM/GAIA" era (BSGE), one needs very precisely defined subsamples of objects (stars) to address very specific questions. After all, as astrophysicists we can not manipulate the subjects of our investigation. We can only do the next best thing: carefully select samples of stars for which only the parameter under investigation varies.

> For example: A) when investigating the magnitude of tidal effects on, say, chromospheric activity, one selects binary stars with A RANGE IN ORBITAL PERIODS and otherwise similar parameters. B) when determining the "Oort Limit," (local density of luminous+dark matter) one needs to select a group of stars WITH SIMILAR AGE and relate their number counts and velocities as a function of z-height to derive the vertical potential.

Second, because so little is currently know about stars, we’d better provide as much information on them as possible so that: A) "OBSS data" can be used to identify research areas of interest (i.e., provide more than parallax & position), B) the "OBSS data" itself lends itself to meaningful sample definition, and C) that the "OBSS data" itself can be used to further investigate the interesting phenomena.

Here I quote "OBSS data" because it might be possible (albeit unlikely) to obtain ground-based spectra of a significant fraction of the OBSS sample. This issue needs further investigation.

At any rate: THE BEST/EASIEST WAY TO PROVIDE LOTS OF ADDITIONAL INFORMATION ABOUT STARS IS TO PROVIDE "OBSS SPECTRA."

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Some Science Requirements for a
Radial Velocities & Spectral Information Survey

A) Radial velocities

- A1-A5 need roughly 10 km/s
- A6 needs better than 1 km/s, i.e., only the brighter/closer ones

1) Multiple radial velocity measurements (10 to 20) are required to determine the orbital parameters of "spectroscopic" binaries that are also astrometrically resolved (~260,000 stars or ~10% of stars within 200 pc). Without this info, parallaxes are severely compromised

2) Eliminate stellar companions as a source of false positive planetary transits

3) Eliminate "close" binaries from samples used in galactic dynamics studies. Binaries add ~5.3 km/s to the dispersion of the population and create high velocity tails (up to 60 km/s) to the apparent velocity distribution.

4) Enable galactic dynamics studies such as: the Oort limit, rotation curve, mass of spiral arms by providing the full 3D space motion of stars.

5) Enable the investigation of the positional dependence (Galactocentric radius and azimuth) of studies listed under A4.

6) Enable study of the full 3D internal dynamics of nearby/bright open clusters. Are all low-mass stars ejected from such systems?

7) Semi-simultaneously determine the "radial velocity" and brightness variations of variable stars such as Cepheids (Peak-to-Peak=70 km/s), RR-Lyras (P2P=150 km/s) and Miras (P2P=30 km/s). Such info is crucial to better understand the pulsation mechanism, but also to use distant stars as tracers of the Galactic potential.

8) etc.

B) Stellar Spectra:

Accurate knowledge of stellar evolution/atmospheres is crucial for our understanding of the properties of stellar primaries of extra-solar planetary systems.

Stellar evolution and the interpretation of stellar spectra depend not only on mass and metallicity, but also on:

1) stellar rotation (needs R>=15,000)

2) abundance peculiarities such as:
   - alpha-element enhancement
   - ratio of r-process and s-process elements
   - abundances of molecules in cool stars

3) Magnetic field strength
   - Find young solar analogs: how does B & rotation vary with time
   - Habitability of early Earth

4) Binarity:
   - resolvability of the primary & secondary components

5) Mass loss
   - On the main-sequence?
   - On the giant branch etc profoundly affects the evolution of the Milky Way: regulation of [Fe/H](time)

6) Chromospheric activity
   - Habitability criterion
   - etc.

7) Emission-line level (H-alpha)
   - Habitability criterion
   - etc.

8) (Spectral) Variability

9) Interstellar absorption
   - Needs to be determined to get stellar parameters
   - etc.

10) etc.

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----------REQUIREMENTS FOR SPECTROSCOPIC OBSERVATIONS----------

"OBSS spectra" might be space-based or ground-based. However, in either case, those spectra should be available at the time when the astrometric data is being processed/released: otherwise ground-based follow-up will be a major bottleneck and will greatly slow-down/reduce the number of publications/results generated by OBSS.

Furthermore, a long time-baseline with many repeat observations is very much desirable because they help to identify the binaries in the sample.

For example, if ~100% of stars are "binaries," which are observed at random orbital phases, the orbital motions change the systemic velocity by: 0.0 +/- 5.3 km/s. That is to say, averaged over a large sample of stars, the mean velocity does not change, while the apparent dispersion of the population is increased. However, the distribution function is highly non-gaussian, with very significant high-velocity tails up to tens of km/s [see De Rijcke & DeJonghe, 2002, MNRAS, 329, 829 for an analytical treatment with similar results].

Also, the more observations are available, the easier it becomes to determine the orbital parameters of close binaries. Spectroscopic orbital parameters are required so as to be able to solve the astrometric orbit as well as the parallax and proper motion.

My calculations presented below suggest that neither OBSS, nor GAIA nor SIM can improve the HIPPARCOS parallaxes of nearby "SPECTROSCOPIC" binaries, unless a period from RV data is available.

Note that these systems are one of the most interesting (and abundant: ~5% of stars) groups to study. After all they are both spectroscopic and astrometric binaries and can thus yield individual masses as well as an independent determination of the parallax.

To obtain as much additional information as possible on the stars, spectra over a wide a band as can be practically achieved must be obtained. The resulting radial velocity accuracy is just one of the criteria. Other important to-be-determined parameters are:

a) stellar rotation (needs R>=15,000)

b) abundance peculiarities such as:
- alpha-element enhancement
- ratio of r-process and s-process elements
- abundances of molecules in cool stars

c) Magnetic field strength

d) Chromospheric activity

e) Emission-line level (H-alpha)

f) (Spectral) Variability

g) Binarity:
- resolvability of the primary & secondary components

h) Mass loss

i) Interstellar absorption

j) "radial" velocity curves that cover the phases of variable objects such as: Cepheids (Peak-to-Peak=70 km/s), RR-Lyras (P2P=150 km/s), Miras (P2P=30 km/s), (eclipsing) binaries, transiting planets, and so forth

----------BINARIES--

Spectroscopic Binaries (SBs):

If one needs N_RV radial velocity measurements to adequately sample the orbital phases and derive the orbital parameters. The work by Munari et al. (2001, A&A 378, 477) suggests that N_RV >~ 20.

Thus "OBSS" needs to produce N_RV observing epochs during a measurement campaign of T_RV years. In other words, systems with periods less than P_max = T_RV*365.25/N_RV days are fully sampled by "OBSS," so that their orbits can be well determined spectroscopically. For T_RV=5 years and N_RV=20, P_max = 91 days.

Given the periods distribution derived by Duquennoy & Mayor (1991, A&A, 248, 485), 9.7% of binaries have P <= 91 days [1.5% with P <=2.5 days, 3.7% with P <= 10 days, 5.2% with P <= 20 days]

As discussed below, the RV data are indispensable for the accurate determination the astrometric parameters.

For example, a system with a G0V primary and a G5V secondary (on the ZAMS) have masses and luminosities of, respectively: 1.05 & 0.92 M_sun and 1.50 & 0.78 L_sun (M_tot = 1.97 M_sun & L_tot = 2.28 L_sun). If such a system has a period of 10 days, the semi-major axis equals:

a_T ~ (1.97*(10/365)^2)^(1/3) ~ 0.114 AU

The primary & secondary have:

a_P = a_T * M_sec/M_Tot = 0.0532 AU
a_S = a_T * M_pri/M_Tot = 0.0608 AU

With velocities of: V_i ~ V_Earth * a_i/P_yr

v_P ~ 30 * 0.0532 * 365/10 = 58.3 km/s
v_S ~ 30 * 0.0608 * 365/10 = 66.6 km/s

At a distance of 10 (100) parsec, such a system would be unresolved by most telescopes as these semi-major axes translate to angular sizes of:

a_T = 11,400 (1,140) muas
a_P = 5,320 (532) muas
a_S = 6,080 (608) muas

Astrometrically, the motion of the photocenter is the observable which is related to the relative brightness of the stars. With:

b_pri = L_pri/L_tot = 0.658
b_sec = L_sec/L_tot = 0.342,

so that the semi-major axis of the photo center equals:

a_phot = a_P * b_pri - a_S * b_sec = 0.0142 AU

= 1.420 mas = 1,420 muas @ 10 pc
= 0.142 mas =   142 muas @ 100 pc

The absolute magnitude of this system would be 0.895 mag brighter than that of the Sun, or M_V = 4.83-0.895 = 3.94, and its apparent magnitudes 3.94 and 8.94 at 10 pc and 100 pc, respectively. At these magnitudes (although too bright to be observed by OBSS-B), the single-measurement accuracies for OBSS-A and -B are 0.180 & 0.125 mas, for mission accuracies of 0.004 & 0.010 mas, respectively.

[For a 2.5 day period, a_T ˜ 0.045 or 2.5 times smaller than for a 10 day period, so that the photocenter is still easily resolved at OBSS' mission-end accuracy. For a 20 day period, a_T ˜ 0.181 AU or 1.6 times larger than for a 10 day period.]

If these binary excursions are not modeled properly, they add "astrometric noise" to the data by increasing the single-measurement accuracy: to

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SQRT(1420^2 + 180^2) = 1431 muas at D= 10 pc (OBSS-A)
SQRT( 142^2 + 180^2) =  229 muas at D=100 pc (OBSS-A)
SQRT(1420^2 + 125^2) = 1425 muas at D= 10 pc (OBSS-A)
SQRT( 142^2 + 125^2) =  189 muas at D=100 pc (OBSS-A)
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Thus, at 10 pc, the systematic error introduced as a result of unmodeled binary motion worsens the position & parallax errors by a factor of ˜1431/180=7.9 [1425/125=11.4] for OBSS-A (-B) at 10 pc. The degradations are 30% and 51% at 100 pc for OBSS-A & -B.

Thus, systems traditionally considered to be SPECTROSCOPIC BINARIES ARE EASILY RECOGNIZED by OBSS/GAIA/SIM AS ASTROMETRIC BINARIES. However, due to the sparse time-sampling of OBSS (once every 10 days for OBSS-A; once every 20 days for OBSS-B & GAIA), these systems have undersampled orbits so that the determination of the period (as well as the parallax and the other orbital elements) is going to be difficult from astrometric-only data. This degeneracy is immediately resolved if the period is provided by the spectroscopic data

------------GALACTIC-DYNAMICS---

Virtually all problems in Galaxy Dynamics can only be solved by the application of statistics. This is so because stellar motions have a sizable intrinsic "random" component. This random component can be tolerably well described by a gaussian distribution with a characteristic dispersion.

Typically, motions of stars are decomposed along three direction defined by either a cylindrical (i.e., disk; R, theta, z) or spherical (i.e., halo; R, theta, phi) coordinate system. The star's peculiar motion (V_pec) is obtained by subtracting the value of the circular motion from the theta-velocity. The amplitude of the peculiar motion is indicative of the type of star/orbit:

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early type stars have small        V_pec
halo       stars have large        V_pec
young disk stars have small        V_pec
old   disk stars have intermediate V_pec
thick disk stars have intermediate V_pec
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Typical dispersions (sigma_v) are 10 km/s for early type stars and 30 km/s for samples of solar-type stars.

----------PRECISION GALACTIC DYNAMICS----------

The current state of affairs in Galactic Dynamics is OK: parameters are known to +/- 10% or so. To make progress (turn the Galaxy in a true benchmark galaxy), things need to be determined ˜10 times better: 1%

To estimate the number of stars that are needed to reach an acceptable level of accuracy, consider the following simple example. To determine the average velocity of an ensemble of stars to X%, one needs

$$N_* = (100/X * \sigma_v)^2 \sim (1/X)^2 * (\sigma_v/30)^2 * 10^7$$

stars.

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10% of sigma_v = 10 km/s (1   km/s) requires     10,000 stars
 1% of sigma_v = 10 km/s (0.1 km/s) requires  1,000,000 stars
10% of sigma_v = 30 km/s (3   km/s) requires     90,000 stars
 1% of sigma_v = 30 km/s (0.3 km/s) requires  9,000,000 stars
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One of the goals of precision galactic dynamics is to determine not only the rotation curve of the Milky Way, but the deviations from a smooth, azimuthally symmetric velocity field. The ability to experimentally determine such local deviations is crucial when trying to measure, for example, the mass associated with the spiral arms. [We are still not quite sure as to whether spiral arms are just regions of enhanced star formation, or an actual density enhancement of the disk. This is evidenced by the fact that in K-band images of spiral galaxies, the spiral arms are often absent/much_reduced].

Furthermore, these properties need to be determined over a large part of the disk so that it will be possible to check whether the spiral arms are caused by a single mechanism, or that several processes are at work, depending possibly on Galactocentric radius.

If regions are found where a different mechanism causes the burst of star formation ("spiral arm"), one would like to determine the initial mass functions in those region. Such research could shed light on our understanding of the star formation process itself as well as help us with the interpretation of high-redshift galaxy images.

Another goal would be to precisely determine the evolution of the Oort "constants" (Olling & Dehnen,2003ApJ...599..275), but then again as a function of position in the Galaxy.

At any rate, one would need the 3D motion of the stellar samples as a function of position in the Galaxy. If only two components are available (from proper motion), the degree to which the true space motion can be recovered depends on position in the Galaxy. That is to say, as longitude and latitude change, the observed proper motions contribute varying amounts to the 3D motions in Galactocentric coordinate system. Thus, the inter-comparison of the local kinematics in different parts of the Galaxy becomes very difficult with pms only. The RVs provide the critical element that allows for such studies.

----------SYSTEMATICS:----------

Because statistics are needed to arrive at conclusions regarding the dynamics of the Milky Way, it is important that the catalogs used are free of systematics at the level one is interested in.

BINARITY:------------------------------

Does not cause a systematic shift in the mean velocity, but does significantly change the shape of the distribution function (adds significant high-velocity tails [up to ~60 km/s]). Thus, for projects that are dependent on the SHAPE of the distribution function (such as the determination of the mass of the stellar disk [Oort Limit]) one needs to know that the "radial velocities" are actually center-of-mass motions, and not affected by binary motion. If not, too large a disk mass will be inferred.

GRAVITATIONAL REDSHIFT:----------------

The gravitational redshift arises when light escapes from the potential well of a star. With M_* and R_* the mass & radius of the star, the gravitational redshift (z_g) is approximately equal to:

$$z_g = G M_* / [c^2 R_*],$$

which leads to an observable redshift of:

$$V_g = 0.638 \, M_*/M_{sun} * R_{sun}/R_* \quad [km/s]$$

with M_{sun} and R_{sun} the mass and radius of the Sun. Employing the zero-age main-sequence mass-radius relation, I find that the lowest mass M-dwarfs have $V_g \sim 0.5$ km/s, while ZAMS stars more massive than 10 M_{sun} have $V_g > 1$ km/s. Obviously, this problem is much reduced when using giant stars to probe the potential of the Milky Way [e.g., Cepheids have $\langle V_g \rangle \sim 50$ m/s].

When using main-sequence stars to probe the Galactic potential, and without correcting for the V_g term, the interpretation of stellar radial velocities leads to significant SYSTEMATIC errors [i.e., a Sun-centered apparent expansion of the Galaxy]. As far as I am aware, galactic dynamicists (myself included) do not correct their radial velocity data for this effect.