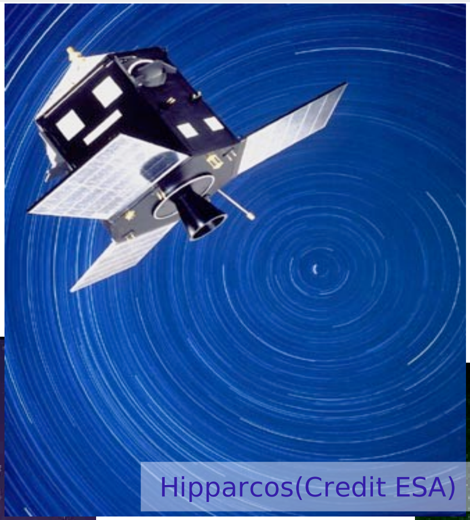
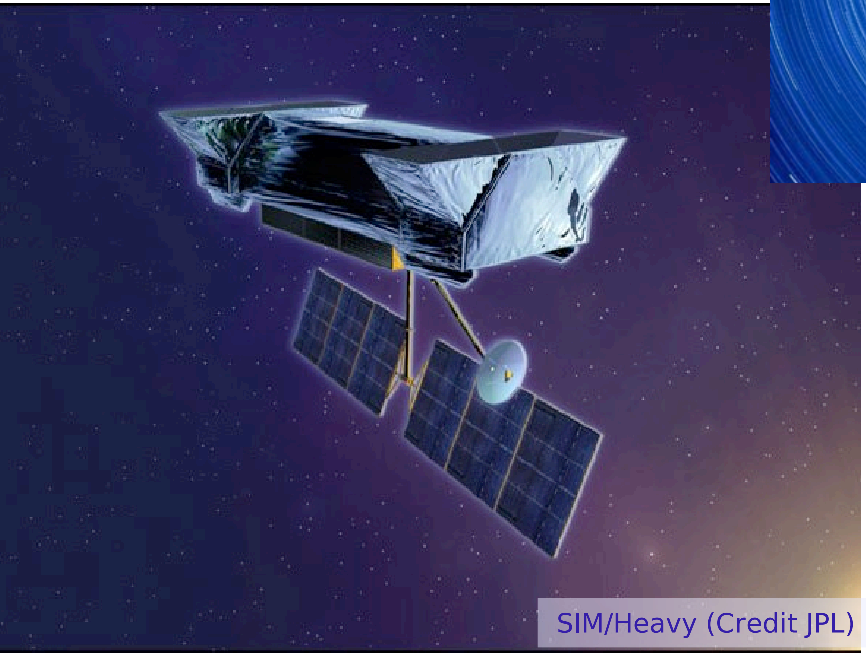
Searching for Solar System Giant Analogs

A SIM Science Studies Project

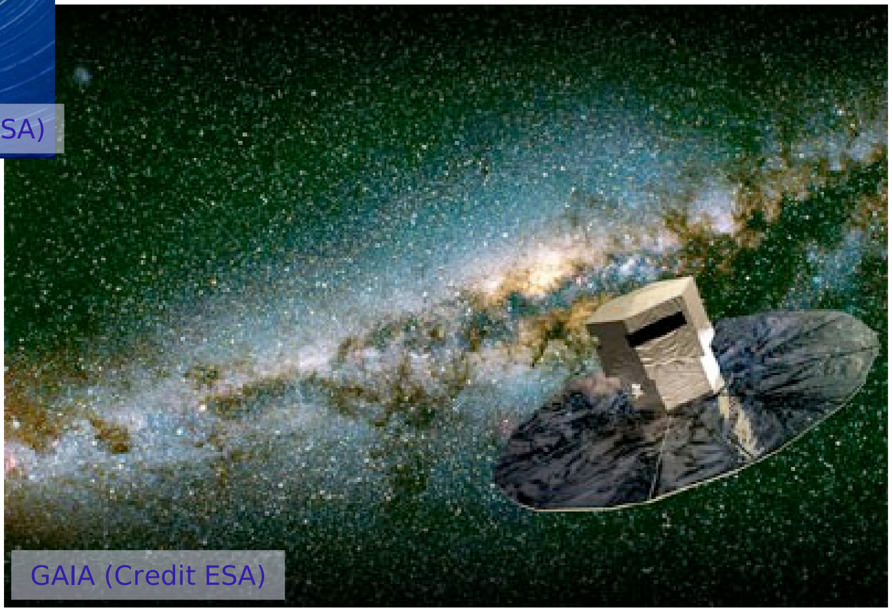
Rob Olling, Ed Shaya (UMd)



Hipparcos(Credit ESA)



SIM/Heavy (Credit JPL)



GAIA (Credit ESA)

Outline

- Astrometric Scales in Astronomy
- Long Period Planets in Solar System & elsewhere
- Observability
- Traditional search methods
  - (μ_B problem)
- Position Differences
  - Hipparcos to the Rescue
  - Period & Mass determination
- Conclusions & Future work
  - Backup slides
    - Part of this talk is based on a contribution to the Extrasolar Planet Task Force [Olling, 2007arXiv0704.3059O]

Astrometric Scales in Astronomy

Parallaxes, in μas		Proper Motions, in μas/yr	
• α Cen:	742,000	• α Cen:	3,600,000
• RR Lyra:	4,380	• RR Lyra:	200,000
• δ Cep:	3,320	• δ Cep:	16,500
•		•	
• 1 kpc:	1,000	• 10 km/s @ 1 kpc:	2,110
• Gal. Center:	125	• 200 km/s @ 8 kpc	5,275
• LMC:	20	• 50 km/s @ LMC:	211
• M 31:	1.5	• 200 km/s @M 31:	60

USA @ 10 pc 2.9 ; 2 M_{EARTH} @ 10 pc: 1 μas/yr

Long Period Objects (Planets, BDs, Stars)

- **For astrometry, velocimetry:**
  need: P_{ORBIT} <~ twice observing span to determine P_{ORBIT}
- **Most of Solar System's angular momentum is in Jupiter & Saturn:**
  - **Solar System Analog**:
    system that has a "Jupiter" and/or "Saturn"
    and/or Uranus/Neptune
- All outer planets have $P_{ORB} > T_{MISSION}$

Planet	AU	Period	Mass
Jupiter	5.2	11.9	318
Saturn	9.5	29.4	95
Uranus	19.2	84.0	15
Neptune	30.1	164.0	17

How Many Long-Period Planets?

- **Which long-period planets:**
  - **S**OSAs: $P \in [11.9, 165]$ yr
    $M \in [0.05, 1]$ M_{JUP}
  - **H**OSAs: $P \in [11.9, 165]$ yr
    $M \in [1, 13]$ M_{JUP}
- Fraction of Planetary Systems:
  [Tabachnik & Tremaine (2002) or Cumming et al (2008)]
  - **SOSAs: 13 %**
  - **HOSAs: (17 +/- 3)%**
- **HOSAs: 8% of Sun-like stars**

Long Period Planets: Where?

- Some Planetary Migration Theories predict
  - Inward migration (known "RV" planets)
  - Outward migration (Uranus & Neptune)
    - Outer edge: 50-100 AU (350 – 1,000 yr) [Ida & Lin, 2004]
  - Predict massive long-period planets
  - Would require more massive disk
- Without migration: 30-40 AU (165-250 yr)
- MUCH, much longer than $2T_{MISSION}$
  - **How to measure this?**

Some Scales

$$a_0 = 95/d_{10pc}\ (P^{+2}\ M_{TOT}^{-2})\ M_{C;J}\quad [\mu as]$$
$$|\mu| = 600/d_{10pc}\ (P^{-1}\ M_{TOT}^{-2})\ M_{C;J}\quad [\mu as/yr]$$
$$|d\mu/dt| = 3800/d_{10pc}\ (P^{-4}\ M_{TOT}^{-2})\ M_{C;J}\quad [\mu as/yr^2]$$

$1M_{JUPITER}$ @ 20 pc			
Period	a_0	$\|\mu\|$	$\|d\mu/dt\|$
[yr]	[μas]	[μas/yr]	[μas/yr²]
5	139	174	219.0
10	220	138	87.0
20	350	110	35.0
40	555	87	14.0
80	881	69	5.4
160	1,399	55	2.2
320	2,221	44	0.9
640	3,525	35	0.3

Standard Orbit Fitting:

5yr

10yr

SIM 3σ Limit:

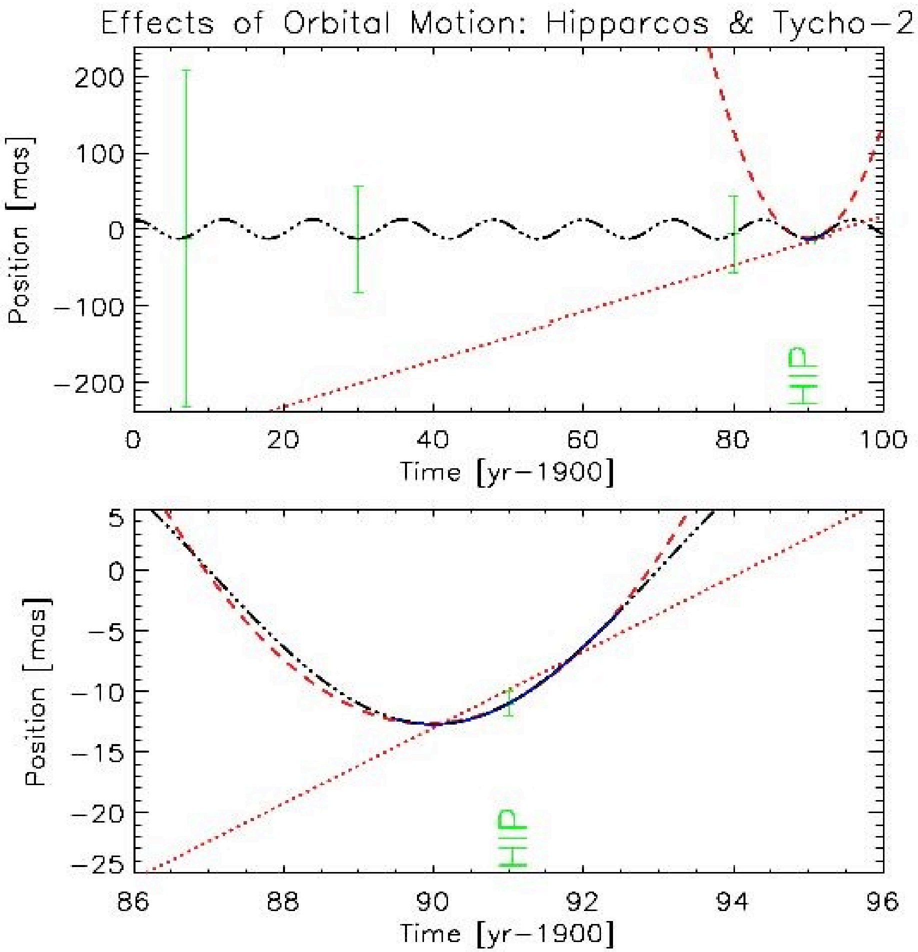
5yr: ~5.1 μas/yr²

10yr: ~1.8 μas/yr²

Finding long-period systems: w. Hipparcos & Tycho-2

- Use information from other astrometric catalogs
  - e.g., **Tycho-2** catalog comprises data from 144 catalogs going back to ~1907
    - Astrographic catalog (1907 @ 220 mas)
    - USNO's AGK2 (1930 @ 70 mas)
    - USNO's TAC (1980 @ 50 mas)
    - **Hipparcos** (1991 @ 1 mas)
    - ...
- Compare pr.-motions in
  - short-period cat (Hipparcos)
  - W. long-period cat (Tycho-2)

Finding long-period systems: w. Hipparcos & Tycho-2



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    - ...

$M=51\ M_{JUP}$; P =12 yr ; D=20 pc

$a_0=12$ mas ; $\mu_{ORBIT}= 6.6$ mas/yr

Traditional Period (&mass) determination

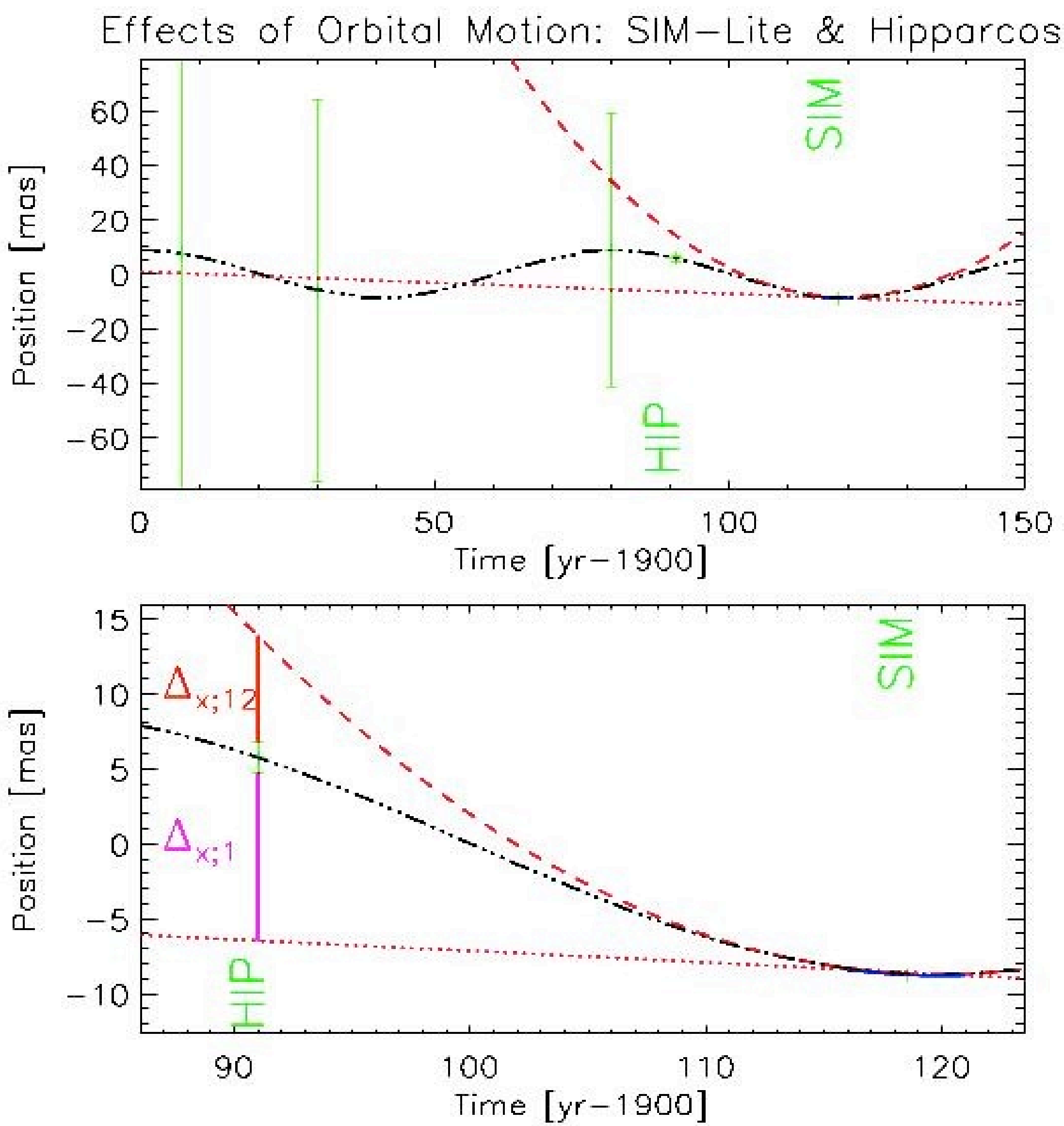
- Total motion (face-on; circular):

  $$z_{TOT}(t) = z_0 + \mu_B\, t + z_{ORBIT}(t)$$

  $$z_{ORBIT}(t) = a_0 \cos(2\pi t/P+\varphi)$$

- Get derivatives:
  - $dz/dt = \mu_B - a_0\,(2\pi/P)\,\sin(2\pi t/P+\varphi)$ [proper motion]
  - $d^2z/dt^2 = - a_0\,(2\pi/P)^2 \cos(2\pi t/P+\varphi)$ [acceleration]
  - $d^3z/dt^3 = + a_0\,(2\pi/P)^3 \sin(2\pi t/P+\varphi)$ [jerk]
- Get Period (Avoid barycenter term)
  - $dz/dt \,/\, d^3z/dt^3 = (P/2\pi)^2$ need: high-order derivative
- If barycentric motion known [Makarov & Kaplan 2005]
  - $(dz/dt - \mu_B) \,/\, d^2z/dt^2 = (P/2\pi)$
  - need: μ_B, with Tycho-2 possible to P~40 yr
  - 50 yr w. SIM, but only to (220 mas/110 yr) ~ 2 mas/yr

Finding long-period systems w. SIM & Hipparcos



M = 10 M_{JUP}
P = 80 yr
D = 20 pc
a_0 = 8.8 mas
μ_{ORBIT} = 0.69 mas/yr

Difference between: backtrapolations:

Linear: $\Delta_{x;1}$

Quadratic: $\Delta_{x;12}$

Eliminating μ_B: Backtrapolates

- Total motion (face-on; circular):

  $z_{TOT}(t) = z_0 + \mu_B\, t + z_{ORBIT}(t)$

  $z_{ORBIT}(t) = a_0 \cos(2\pi t/P+\varphi)$

- Expand $Z_{ORBIT}(t)$
  - $\zeta(t)/a_0 = \cos(\varphi) - (2\pi/P)\sin(2\pi t/P+\varphi)t - ½\,(2\pi/P)^2 \cos(2\pi t/P+\varphi)t^2 + \ldots$
  - $Z_{TOT}'(t) = Z_0 + \mu_B\, t + \zeta(t)$

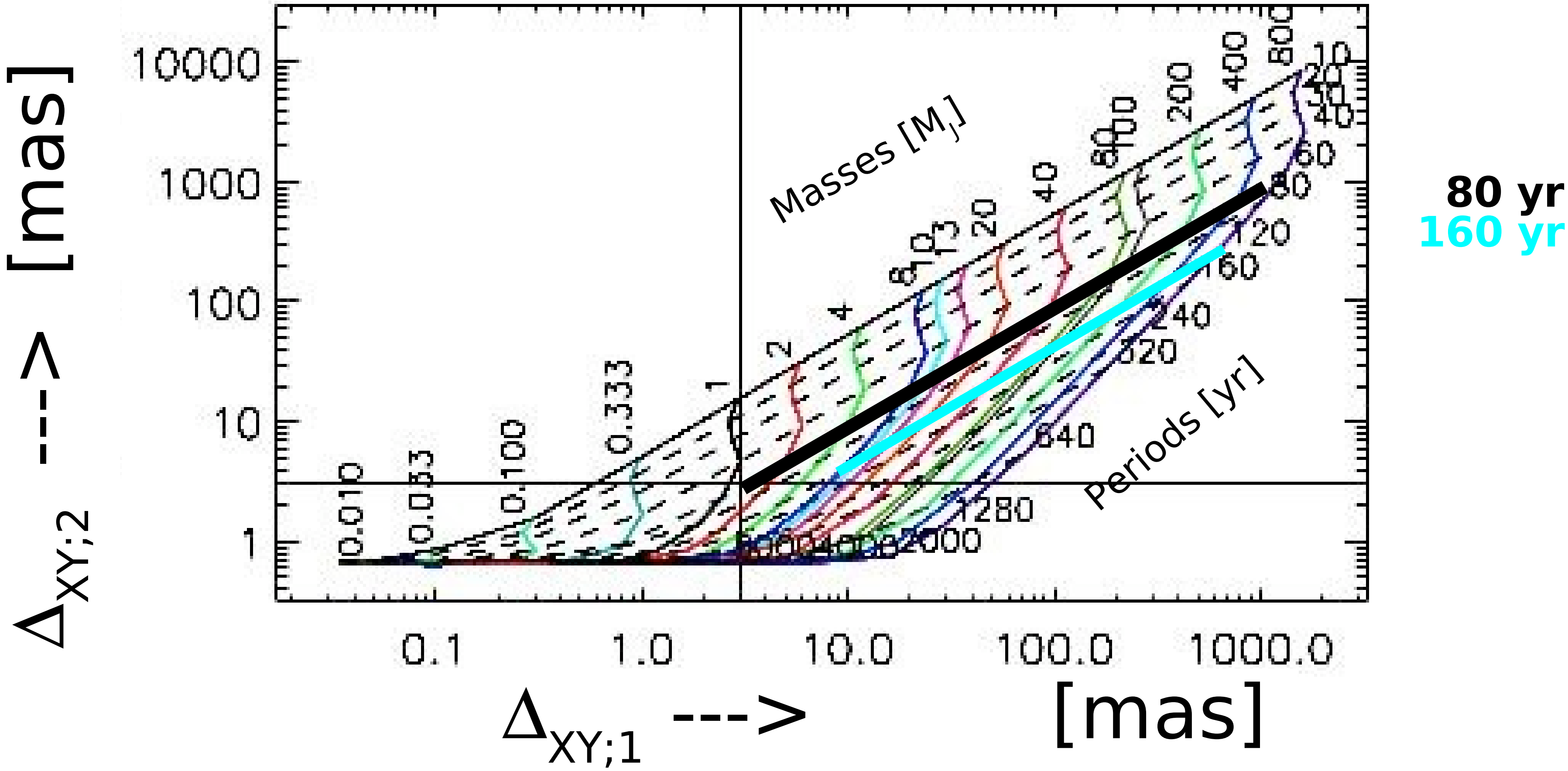
    = n^{th} order polynomial fit to SIM data

- Position Difference at Hipparcos epoch (τ)
  - $\Delta_z(\tau) = z_{TOT}(\tau) - z_{TOT}'(\tau) = z_{0RBIT}(t) - \zeta(\tau)$

- **INDEPENDANT of Barycentric motion**

Backtrapolates: Sensitive to Mass & Period

- **Order-dependent:** $\Delta_{z;n}(\tau) = z_{ORBIT} - \zeta^{n}(\tau)$
  - Can be calculated analytically
- No phase dependence for TOTAL pos. dif.
  - Face-on & circular: $\Delta_{XY;n} = (\Delta_{X;n}^{2} + \Delta_{Y;n}^{2})^{½}$
- **Periods** can be estimated from $\Delta_{XY;n}$ values
  - $\mathcal{P}_{1,2} = 2/3\ \pi\tau\ \Delta_{XY;1} / \Delta_{XY;2}$ ~ P for $P \geq 2\tau$
  - $\mathcal{P}_{2,3} = 1/2\ \pi\tau\ \Delta_{XY;2} / \Delta_{XY;3}$ ~ P for $P \geq 2\tau$
    - $\mathcal{P}$ ~ P for $P \ll \tau$
    - $\mathcal{P}$ oscillates strongly for P ~ [0.5, 1] x τ
    - $\mathcal{P}$ decays (exponentially) towards P for P ~ [1 , 2] x τ
- **Masses** follow immediately once P is known



- 144 SIM positions @ 15.9 μas & Hipparcos
  - 1 M_J and up; P <~ 80 yr
  - 13 M_J and up; P <~ 160 yr
- Improved Hipparcos @ 1/3 mas: twice better
- **Detection** w. $\Delta_{XY;1}$(13M_J): P <~ 400 yr

Conclusions & Future Work

- Position Difference Powerful New Tool
  - To find long-period objects
    - Samples in the migration-cutoff regime (100s of years)
- Need to develop method for generalized orbits
  - Expectations are:
    - Inclination not too important
    - Eccentric orbits: manageable [MK2005]
    - Orbit fitting employing historical data?
- Realistic observing time estimates
  - Local reference frames?

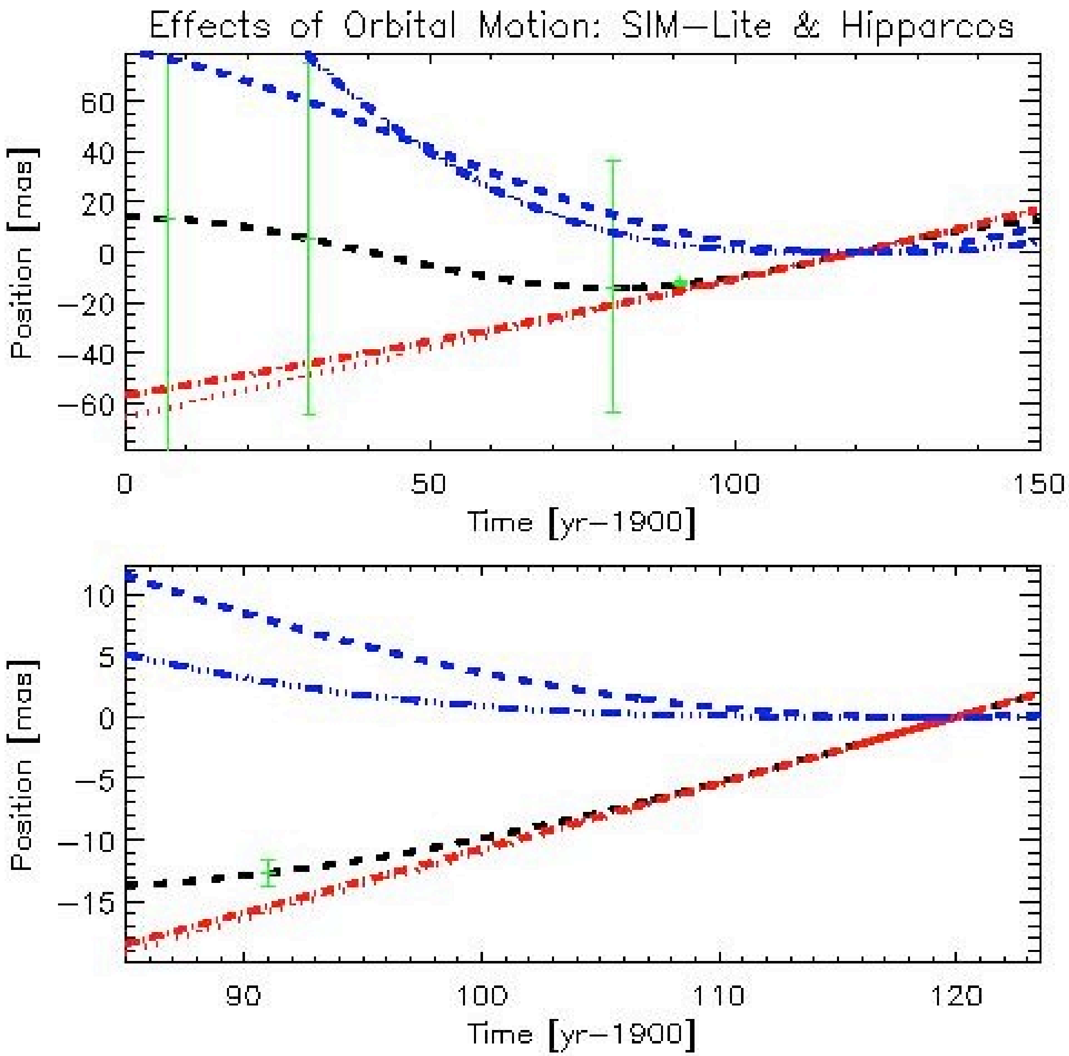
Backup Slides

The Future of Astrometry-enabled Astrophysics (in the US?)

- **Gaia flies before SIM-Lite!**
  - ==> there will be many (10,000's) interesting objects too look at with SIM to get better data
- **Is there going to be dedicated US funding to work with Gaia data?**
  - This would be required to prepare GAIA-follow-up SIM-Lite programs
- **Would it be useful to upgrade SIM-Lite?**
  - Make a larger difference with GAIA
  - Deal with the GAIA follow-up (faster for faint sources)
  - Improve extra-galactic capabilities
- **Are DARWIN & TPF-I potential SIM follow-up?**

- How to estimate SIM acceleration accuracy???
  - Maybe like this? $d\mu/dt \sim (\mu_1 - \mu_2)/\tau$
    - **5 yr Mission:**
      - Split observing span in two 2.5 yr segments, separated by τ=(T/2) =2.5 yr
        - Each have ½ data ==> $\varepsilon_{\mu 5} * \sqrt{2}$
        - $\varepsilon_{d\mu/dt}^2 = [(\sqrt{2}\varepsilon_{\mu 5})^2 + (\sqrt{2}\varepsilon_{\mu 5})^2] / (T/2)^2$
        - $\varepsilon_{d\mu/dt} = (\sqrt{8})/T\ \varepsilon_{\mu 5} \sim 0.56 \times 3 \sim 1.7\ \mu as/yr^2$
    - **10 yr Mission:**
      - Split observing span in two 5 yr segments, separated by τ=(T/2) =5 yr
        - Each have 100% of 5-yr data ==> $\varepsilon_{\mu 5}$
        - $\varepsilon_{d\mu/dt}^2 = [(\varepsilon_{\mu 5})^2 + (\varepsilon_{\mu 5})^2] / (T/2)^2$
        - $\varepsilon_{d\mu/dt} = 2/T\ \varepsilon_{\mu 5} \sim 0.2 \times 3 \sim 0.6\ \mu as/yr^2$
    - **Gaia 5yr:**
        - $\varepsilon_{d\mu/dt;GAIA} = 5/3 \times \varepsilon_{d\mu/dt;SIM} \sim 2.8\ \mu as/yr^2$
        - No follow-up
  - Position accuracy at t_{HIP} (ΔT=25 yr)
    - Pro. motion: $\Delta_{Z;1} = \Delta T \times \varepsilon_{\mu 5} = 25 \times 3 = 75\ \mu as = \Delta_{HIP}/13$
    - acceleration: $\Delta_{Z;2} = ½\ \Delta T^2 \times \varepsilon_{d\mu/dt} = ½\ 25^2 \times 1.7 = 531\ \mu as = \Delta_{HIP}/2$
      - At ACT(1907;ΔT=110 yr) -> $\Delta_{Z;1}/\Delta_{Z;1;ACT} = 0.002$; $\Delta_{Z;2}/\Delta_{Z;2;ACT} = 0.05$;

Finding long-period systems w. SIM & Hipparcos



$M = 10 \quad M_{JUP}$

$P = 160 \quad yr$

$D = 20 \quad pc$

$a_0 = 14 \quad mas$

$\mu_{ORBIT} = 0.55 \quad mas/yr$

Stellar Ages & Astrometry

- Astrophysics of stars is primarily based on:
  THE SUN
  - Fundamental parameters well determined:
    Mass, Radius, Luminosity, He-abundance (Y), [Fe/H]
  - ~100 Binaries with M and R better than 1%
    - but see: Kurucz' **"Some things we do not know about stars"** (2002nqsa.conf....3K)
- M, R, [Fe/H] and Y "set" the rate of evolution
    - Precise Age Determination of Individual Stars
- ⇒ **Detailed Formation History of Galaxy**
    - Star Formation + **Oldest Stars (< age of Universe?)**
  - ⇒ **Galaxy Formation & Cosmology**

Stellar Ages & Astrometry (cntd)

- Rate of Evolution

  – Luminosity: $(\Delta L/L)^{theory} \sim$ $(10 + 2\ L/L_{\odot}) \pm 5$ [% / Gyr]

  Age: $\Delta\tau^{theory} = (\Delta L/L)^{obs} / (0.1 + 0.02\ L/L_{\odot})$ [Gyr]

  $= (2\Delta\pi/\pi)^{obs} / (0.1 + 0.02\ L/L_{\odot})$ [Gyr]

- **Mid G-type stars : $(\Delta L/L) \sim 10$ %/Gyr**
- **Hipparcos**: $(\Delta\pi/\pi)^{obs} \sim$ (1 mas / 100 pc) $\Rightarrow$ **$\Delta\tau^{theory} \sim$ 1,800 Myr**
- **SIM** : $(\Delta\pi/\pi)^{obs} \sim$ (5 μas / 100 pc) $\Rightarrow$ **$\Delta\tau^{theory} \sim$ 9 Myr**

  SIM @ 1 kpc $\Rightarrow$ **$\Delta\tau^{theory} \sim$ 90 Myr**

  SIM @ 5 kpc $\Rightarrow$ **$\Delta\tau^{theory} \sim$ 450 Myr**

  SIM @ 10 kpc $\Rightarrow$ **$\Delta\tau^{theory} \sim$ 900 Myr**

- **Ages are model-dependent**

  Will be calibrated with highly accurate GAIA/SIM, Seismology & Ground-Based data

Stellar Ages: GAIA and SIM

- **NEED RADIUS** ⇒ **Eclipsing Binaries** (~ 1% of Population)
  - Photometry ⇒ $\mathbf{R}_*$, m_V, A_V
    Spectroscopy ⇒ V_{ORB}, $\mathbf{M}_*$ & **[Fe/H]**
    Astrometry (π) + m_V & A_V ⇒ **Luminosity**
    TWO stars on same Isochrone ⇒ Age & Helium
    [Ribas (2006ASPC..349...55R), Lebreton (2005tdug.conf..493L), Lastennet (2002A&A...396..551L); Metcalfe etal (2006ASPC..349...55R)]

- GAIA is survey mission will determine overall SF History
  ≤ 600 pc has $\Delta\pi/\pi \leq 1\%$ for G7 star (V~14.5)
  ~ 6,254,000 thin-disk stars ⇒ ~190,000 EBs ⇒ $\Delta\tau$ ~4 Myr
  ~ 385,000 thick-disk stars ⇒ ~12,000 EBs ⇒ $\Delta\tau$ ~5 Myr
  ~ 12,000 spheroid stars ⇒ ~300 Ebs ⇒ $\Delta\tau$ ~9 Myr

- SIM should do the rare Special Cases at larger distances
  Binary cousins of **Old Uranium Stars** with [Fe/H] ~< -3
  $\tau \sim 13.2 \pm 2.7$ Gyr HE 1523−0901, d ~ 1 kpc, V~11 [Frebel et al 2007]
  $\tau \sim 14.9 \pm 3.0$ Gyr CS 22892-0529, d~ 1.5 kpc, V~12 [Sneden et al 1996; Hill et al 2002]
  $\tau \sim 13.2 \pm 2.7$ Gyr HE 1424-0241, d ~ 8 kpc, V~14 [Cohen et al 2007]
  [See Beers & Christlieb 2004, ARA&A for a review]