Astrometry I

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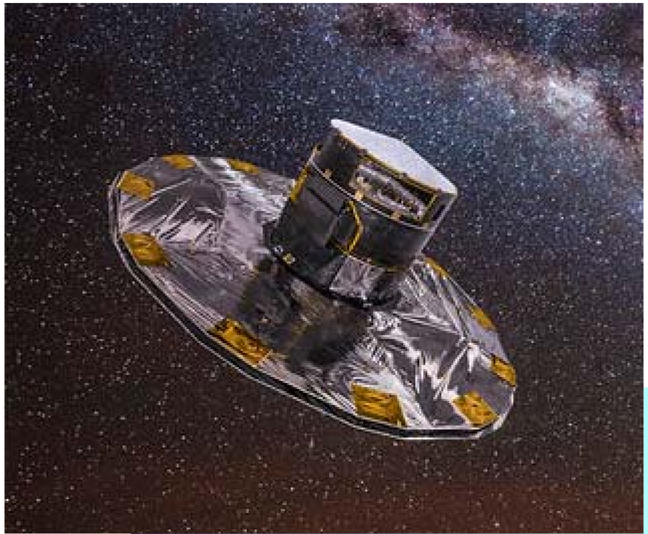
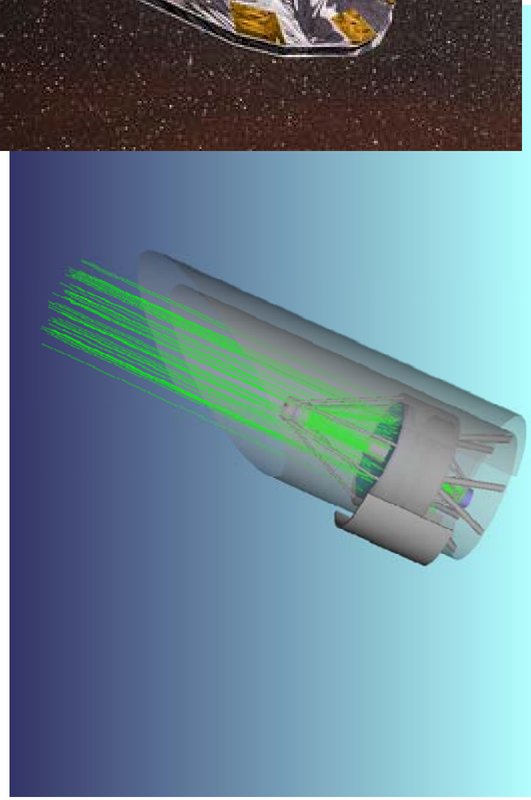
Outline

- Relative astrometry vs Global Astrometry
  - What’s the science objective?
  - What’s possible, what are fundamental limits?
- Instrument Description
- Error/noise sources
  - Photon noise (and detector noise)
  - Instrumental errors
    - Detector errors
    - Optical errors
- Telescope/instrument requirements
- From measurements to science
  - Local reference frame
  - Differential astrometry
  - Detecting Planets/

Global and Relative Astrometry

- GAIA is an absolute astrometry mission. (position of all objects in a global reference frame, tied to Quasars.)
  - Launched 12/2013, start of science operations 6/2014
- STEP (and NEAT) are relative astrometry missions.
  - Position of the target (star) is measured relative to nearby reference stars.

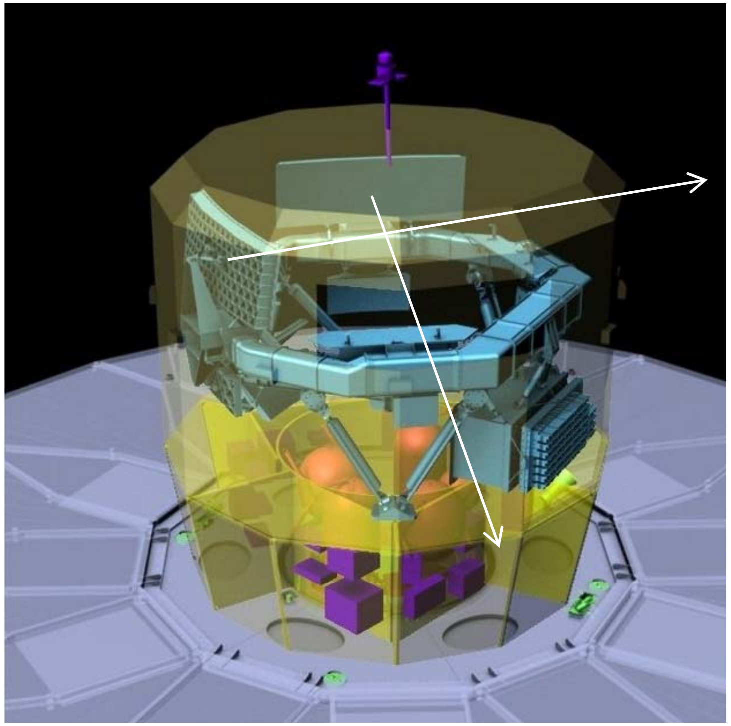


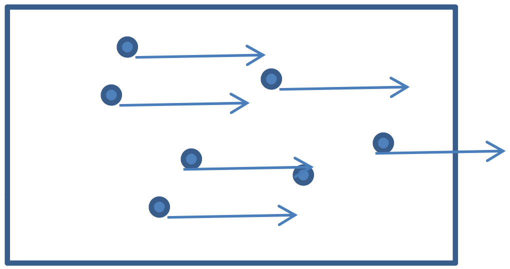


Global Astrometry Science/GAIA Instrument

- GAIA consists of 2 telescopes looking at 2 fields of view ~106.5 deg apart. It scans the whole sky to measure the positions of all objects brighter than 20 mag.
  - While there are two telescopes, they share the same focal plane ~1e9 pixels
- Because the satellite is constantly spinning, the stars are constantly moving across the focal plane.
  - The CCDs are read out in what is call TDI mode. The charges are shifted at the spin rate of the satellite.
  - Producing images of the stars in the sky as they move across the focal plane

The optical design of the GAIA telescope is a TMA same as STEP.

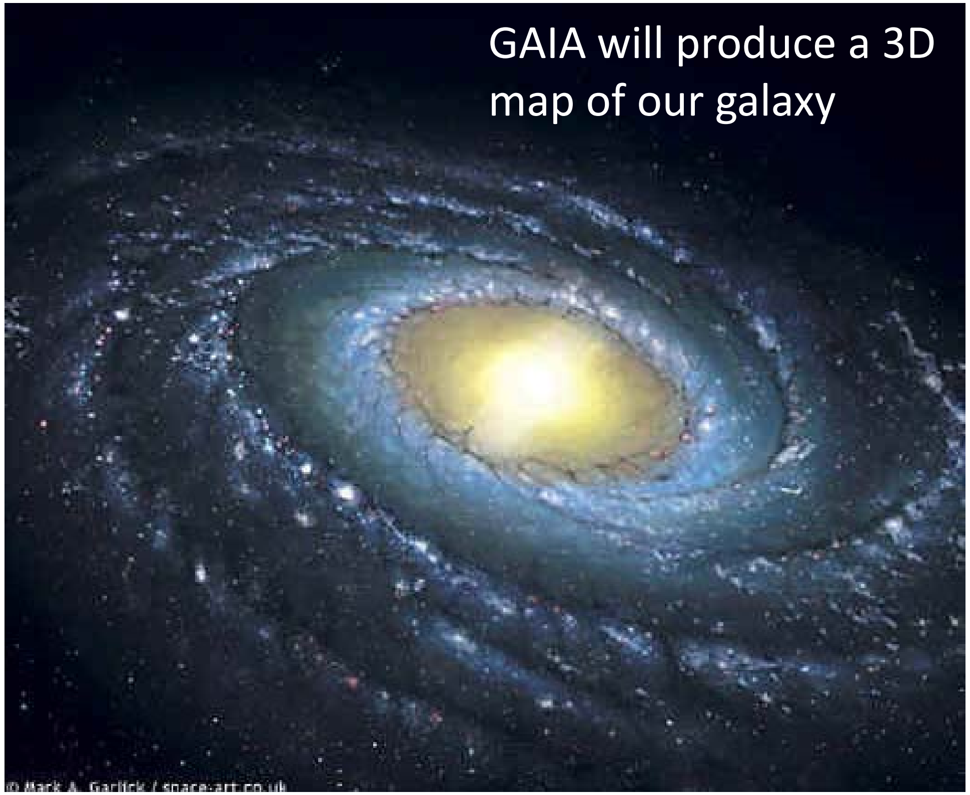




Stars move due to S/C rotation CCD shifts charge at same rate.

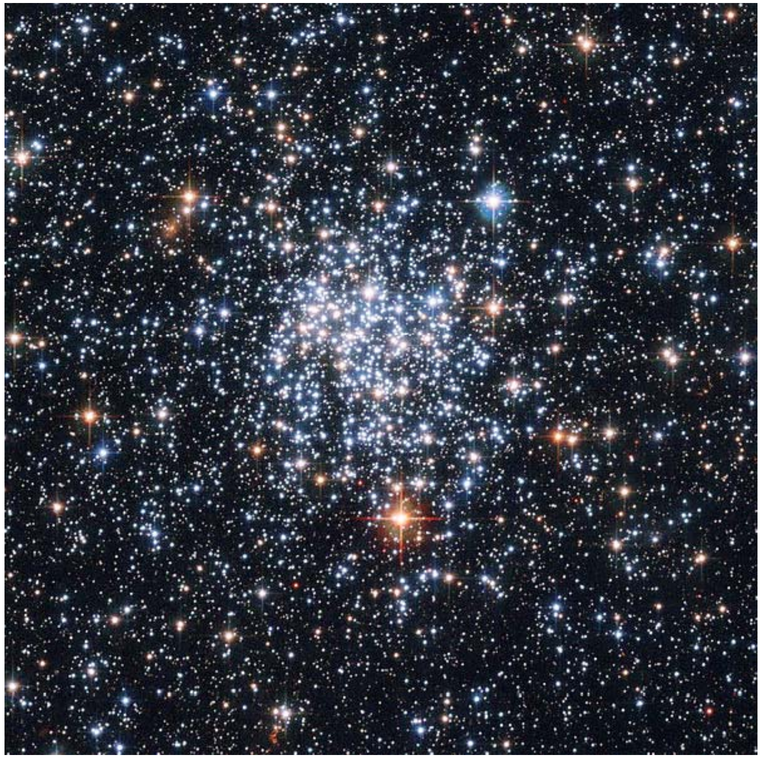
Global Astrometry Science

- Absolute positions of objects. (colocation of objects that emit in the visible, radio, xrays, etc.) (~10 uas after 5yr mission)
- Absolute parallax. Distance to stars. GAIA will produce a 3D map of ~1 billion stars in our galaxy. (~10 uas after 5yr mission)
  – Distances to standard candles (Cepheids, RR Lyrae) will be directly measured.
- Absolute proper motion. The motion of dwarf galaxies, globular clusters around our galaxy will be measured.



STEP/Relative Astrometry

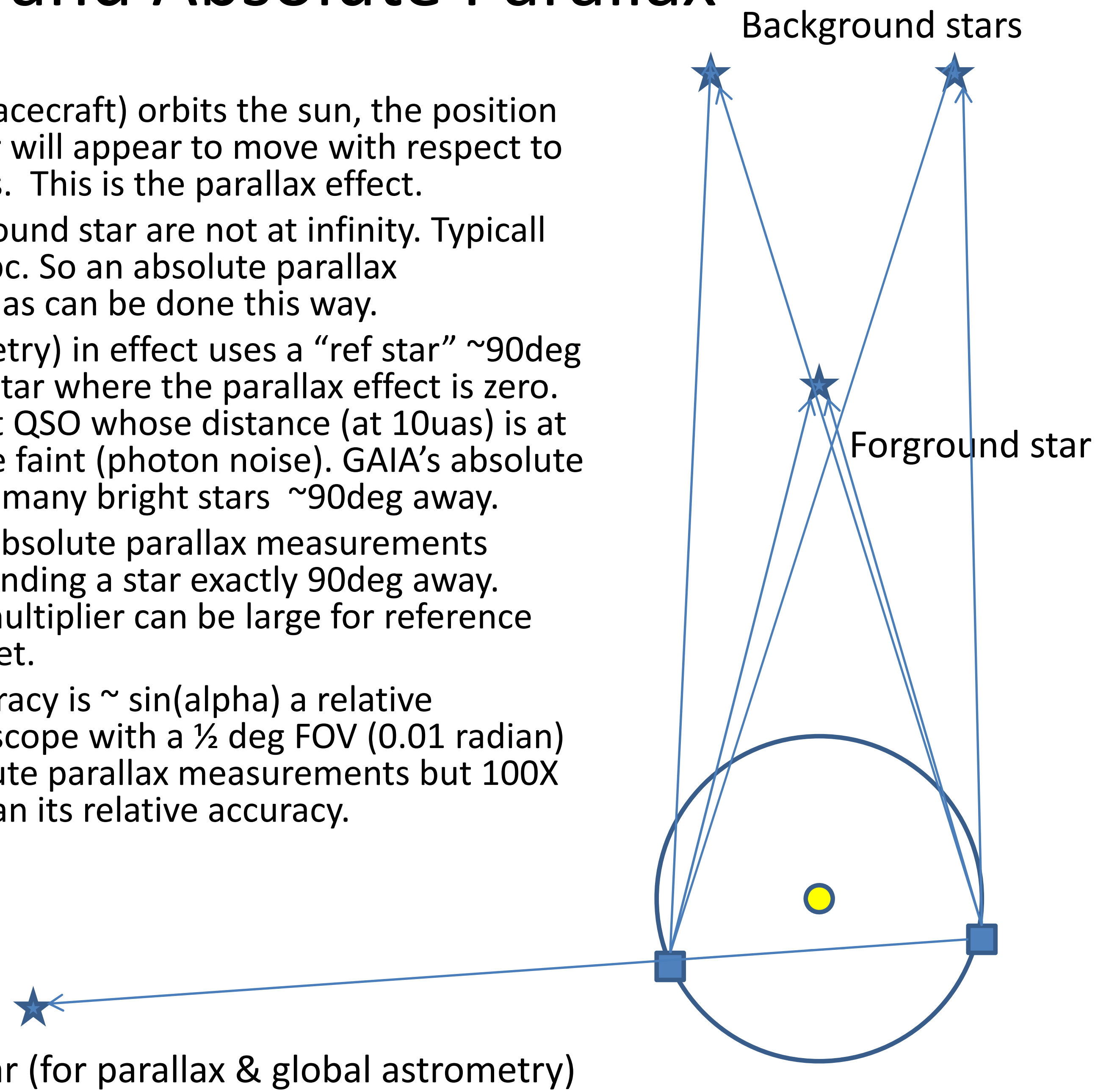
- STEP (and in Europe NEAT) is a relative astrometry telescope
  - ~0.5 deg FOV
  - Goal of ~1 uas precision in 1 epoch. 100 measurements over 5 years would yield precision of 0.1 uas. (compared with GAIA's ~10uas after 5 years.)
  - Narrow angle/relative astrometry, because it doesn't cover the whole sky can not make "absolute" position measurements. But the relative positions usually are measured with higher accuracy than in global astrometry
- Periodic motion of an object can be measured. (Exoplanets, binary stars, binaries where one component is a Neutron star or black hole.



Measurements such as proper motion are usually not meaningful, the background stars used as references are in our galaxy and will have a proper motion typically ~ 1mas/yr.

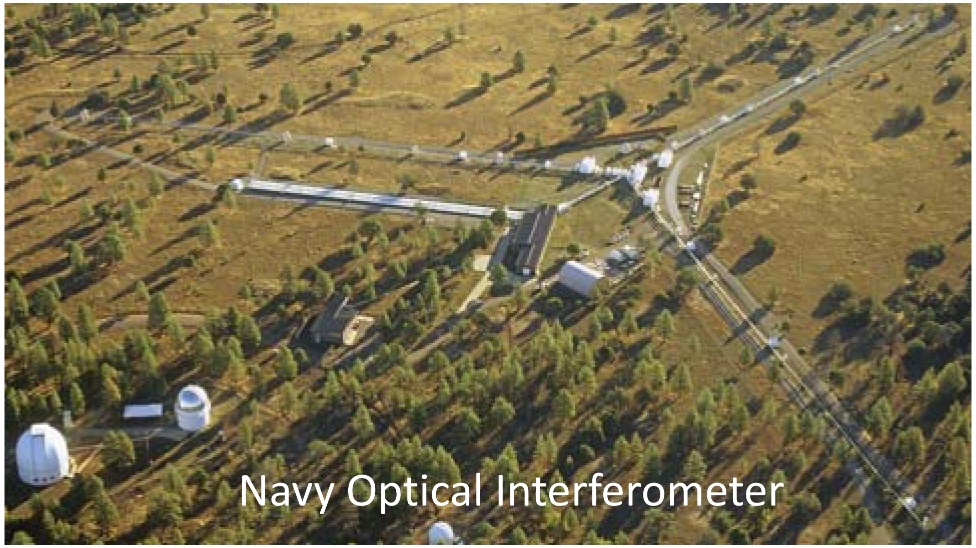
Relative and Absolute Parallax

- As the Earth (or a spacecraft) orbits the sun, the position of the forground star will appear to move with respect to the background stars. This is the parallax effect.
- However the background star are not at infinity. Typicall no more than 1~2 Kpc. So an absolute parallax measurement at 10uas can be done this way.
- GAIA (global astrometry) in effect uses a “ref star” ~90deg from the forground star where the parallax effect is zero. GAIA will also look at QSO whose distance (at 10uas) is at infinity. But QSOs are faint (photon noise). GAIA’s absolute parallax comes from many bright stars ~90deg away.
- The ability to make absolute parallax measurements doesn’t depend on finding a star exactly 90deg away. However the error multiplier can be large for reference stars “near” the target.
  - The loss of accuracy is ~ sin(alpha) a relative atsrometry telescope with a ½ deg FOV (0.01 radian) can make absolute parallax measurements but 100X less accurate than its relative accuracy.



Ground/Space Astrometry

- There’s room for improvement in ground astrometry, but what has been demonstrated is not that far from the limits imposed by atmospheric turbulence.
- Wide angle astrometry, USNO long baseline interferometer (Flagstaff Az) ~ 5mas.
- Narrow angle astrometry, best ground results ~0.5mas Palomar. And Carnegie. Perhaps a bit better for very small fields of view (globular clusters)

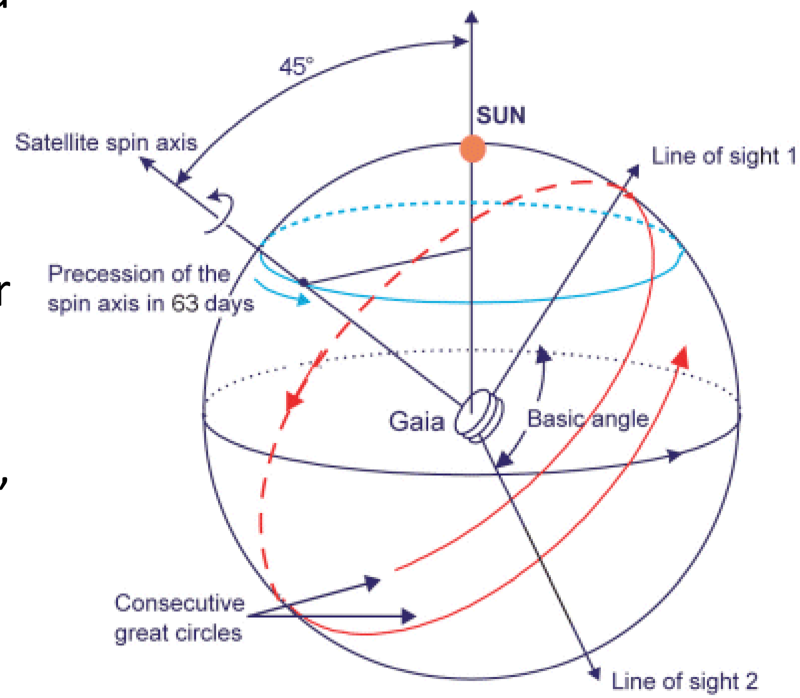


Space, global astrometry
Hipparcos 1991~1997 1mas
GAIA (launch 2013) catalog 2020 7~10uas
GAIA science ops to start June 2014

Narrow angle
STEP 1uas (in ~ 1 hr) 0.05~0.1uas over 5yrs.

Space Astrometry/GAIA

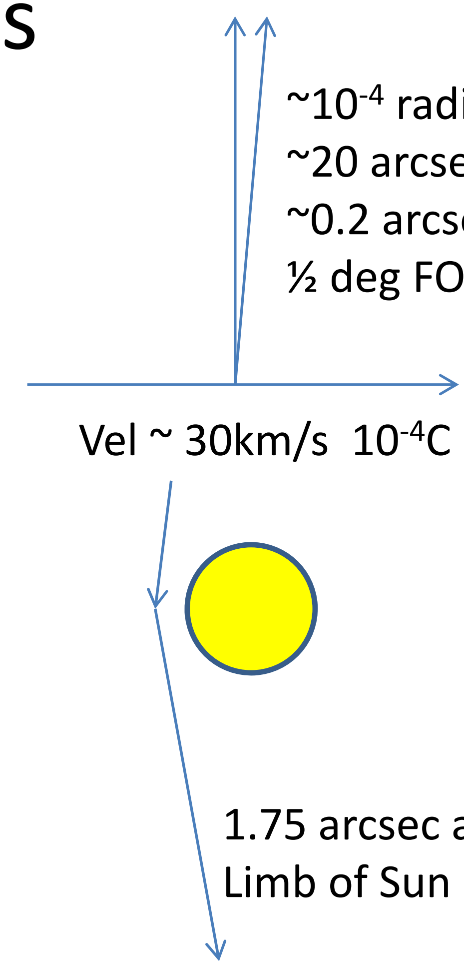
- What data will GAIA produce, and how can one use that data to find exoJupiters?
- As GAIA spins, it scan across the sky and measures the position over every star (in the direction of motion)
- The spin axis precesses and eventually the whole sky is scanned.
- Stars will be scanned 75~150 times over 5 years.
- The data processing centers will produce "standard" data products, (α,δ, π, Pmα,δ)but the scientists looking for exo-jupiters will have to work with the individual scans of the stars they're interested in.
- Each scan only measures 1 Coordinate of the star's position.



Gaia observation principle

Relativistic Effects

- The motion of the Earth (and spacecraft orbiting the Earth) around the Sun will cause the apparent position of the stars to move.
- Special relativity - Stellar abberation (the angular version of the doppler effect)
  - Over a small FOV, differential stellar abberation
- General Relativity – The gravity of the Sun causes the light from a star to "bend" depending on



Accurate astrometry requires relatively accurate knowledge of the velocity of the telescope wrt the solar system barycenter. As well as the position of the Sun, and also the position of Jupiter, earth and moon for stars "near" these objects.

4.1 mas 90deg from Sun effect ~ M/R

350 uas due to Earth at Surface of Earth

Outline II

- From measurements to science
  - Local reference frame
  - Differential astrometry
  - Detecting Planets

Issues with Relative Astromety

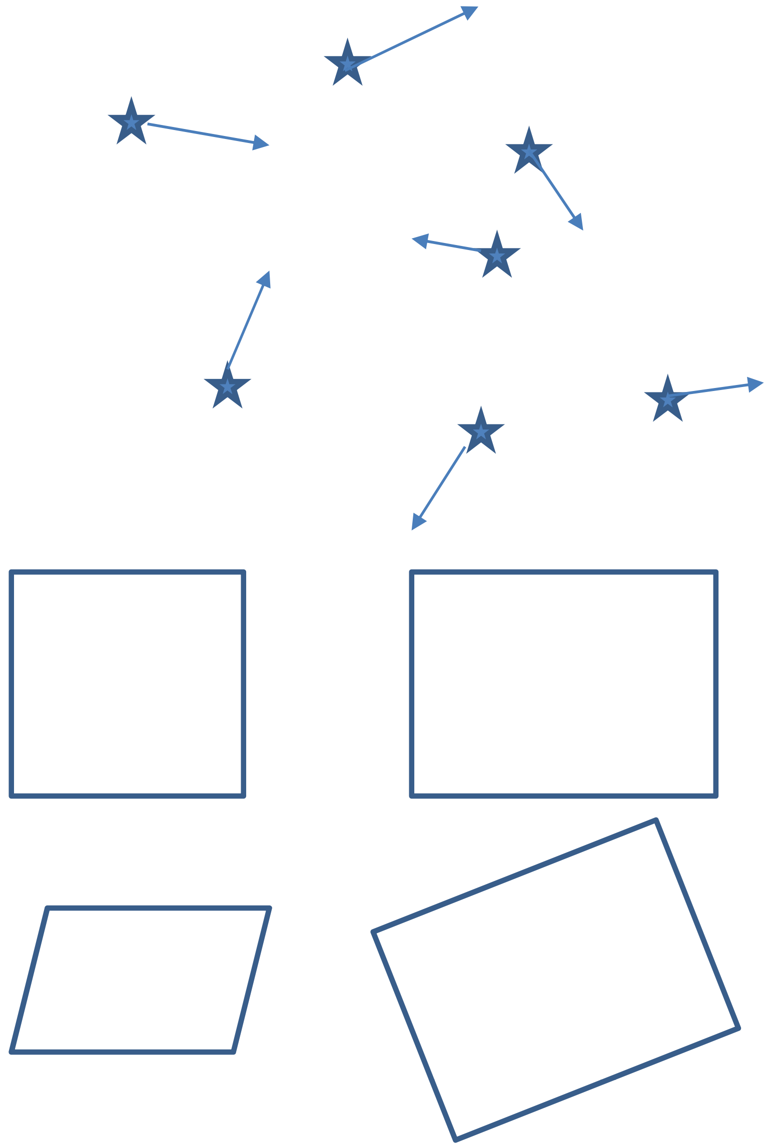
- The most accurate astrometry is relative astrometry, measuring the angles between nearby stars.
- In addition to relativistic effects, one has to consider other potential biases that occur in relative astrometry.
  - Background/reference stars are not at infinity.
  - Parallax effect may mask orbit explanets whose period is 1.00 years.
  - Reference stars have proper motion and parallax
  - Reference stars may have their own planets

Reference Stars at finite distance/motion

- When we look in the sky, the vast majority of individual stars we see are all in our galaxy, relatively nearby.
  - Looking out of the plane of the milky way galaxy, we see stars out to ~1Kpc. (the galaxic disk is ~2 Kpc thick)
  - Looking in the plane of the galaxy, we see stars out to a distance of ~2 Kpc except for a few "holes" in the dust.
    - Interstellar dust absorbs starlight and blocks the light from stars in most cases for stars > 2Kpc away.
- As a result referece stars (especially bright reference stars (~12~14 mag)) all withing 1~2 Kpc.
  - This means that they have parallax effects ~0.5mas. Their motion orbiting around the center of our galaxy will produce proper motions of ~1mas/yr.
- How does this affect relative astrometry?

Distortion of Reference Frame

- For a given solid angle in the sky, there are more distant stars than nearby stars.
  - Most reference stars are 500~2Kpc away.
- Their motion will exhibit a correlated component, (from galactic rotation) and a random component.
- Because of interstellar dust extinction it is difficult to accurately estimate their distance from photometry and spectroscopy.
- What does the motion of ref stars to the ref frame for narrow angle astrometry?



Search for Periodic Motion

- In the search for exoplanets, we're looking for a periodic motion of the target star caused by the orbit of a planet around the star. (or by a neutron star orbiting a normal star in a NS-Star binary)
- The distortion of the reference frame will not mimic a periodic motion.
- There is one potential problem however.
  - If the target star has a long period Jovian planet, a period much longer that the mission lifetime, a "small" rotation of the reference frame can mimic a partial orbit.
  - One of the main advantages of combining space astrometry data with a long term RV monitoring program, is that a 20 yr RV program might identify long period Jupiters.
- But for terrestrial planets with periods << a 5 yr mission there should be no confusion of short period planets with rotation of the ref frame due to motion of the ref stars.
  - If the FOV of the narrow angle astrometric telescope is 20 arcmin, then a proper motion of 1 mas/yr over 5 years, would cause the ref frame to rotate ~ 1 arcsec. A Jupiter mass planet with a 20 yr period would cause arc that covered ~90deg.
  - 99+% of the time, rotation of the ref frame from ref star proper motion is not a problem.

Summary (Relative Astrometry)

- Relative astrometry can not measure "proper motion"
- Relative astrometry has an error multiplier when measuring absolute parallax.
  - If the relative astrometric accuracy is 1uas, relative parallax would be measured to 1uas but absolute parallax to 1 uas/FOV (FOV in radians).
    - A 0.5 deg FOV, would have a ~100X reduction in absolute parallax accuracy.
- When solving for periodic motion (explanets, Neutron star orbits etc) one has to explicitely model the proper motion and parallax of the ref stars, instead of assuming they are at infinity.
  - Even when this is done the absolute proper motion and parallax of the target star can have large biases.
  - However this should not affect the detection of planets whose orbital periods are shorter than the mission lifetime.

Other Astrophysical Effects

- Stellar activity, a star is not a uniformly disk of hot gas @ 4000~10,000K
- The star rotates, and material is ionized (plasma) and is strongly affected by magnetic fields, some generated by the rotation of the star.
- On the sun this is sometime called solar weather, the activity on the surface of the Sun has some analogy with weather in our atmosphere. However, the presence of very strong magnetic fields, and the interaction of the plasma with those fields produce phenomena that we don't see in terrestrial weather.
- Stellar activity disrupts what astronomical instruments detect in most exoplanet search techniques.
  - Transit (stellar noise affects the detection of small exoplanet transits.)
  - RV (stellar noise introduces RV noise that limits the detection of small planets)
  - Microlensing (affected the least, because microlensing only looks for large photometric variations)
  - Astrometry (2^{nd} least affected by stellar activity) more details later

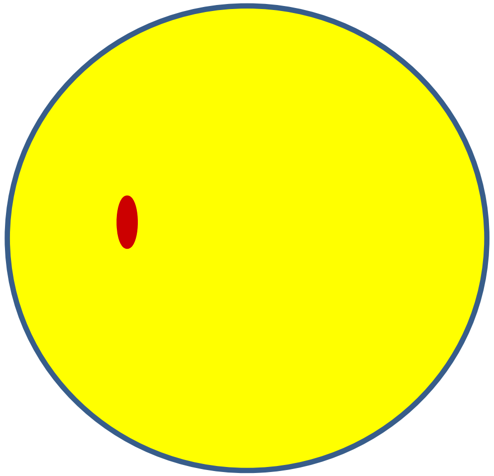
Radial Velocity Search for Earths
RV signature of Earth 9cm/s

- The Swiss team with HARPS on an ESO 3.6m telescope have the most accurate and most sensitive RV instrument, perhaps accurate to 0.5m/s. They are building Expresso for the VLT with the goal of 10cm/sec, (operational in ~2014). They have plans for the ESO ELT(42m telescope). Will RV find Earths?
- Issues with RV (Photon noise, stellar noise)
  - Kepler has found 1235 planet candidates. <20 have been verified by RV follow up. (phot stats and telescope time)
  - Even with Expresso on the VLT, a very large amount of time will be needed. (Udry ~30cm/s in 15 min on 8m telescope) 100 hrs/ target. A search would require a dedicated 8m telescope (100% time) (in Northern and Southern hemisphere)
- More serious problem is stellar noise

Stellar Activity

- There are many types of stellar activity that produces a RV signature but no astrometric signature
- Radial pulsations.
- Many high order modes (5 min oscillations)
  - Strictly speaking there is an astrometric signature, but it is very much attenuated. (the vertical motion of the gases at many km/s is vastly larger than the parts per million (and associated nano arcsec) photometric/astrometric signatures.
- We discuss in slightly more detail, the effect of star spots.

Impact of Star Spots on Astrometry and RV



Example:

Spot area 10^{-3}, Sun @ 10pc

	Astrometry	RV
Spot bias	0.25 uas	1 m/s
Earth @1AU amp	0.3 uas	0.1m/s

$Total\_noise^2 = Instrument^2 + Photon^2 + Stellar\_N^2$

Time scale: Instrument sqrt(T) till systematic

Photon sqrt(T)

Stellar sqrt(T/ ~1 week)

- Star spots produce astrophysical noise that is ~12 times worse for RV than for astrometry. (For an Earth in a 1 yr orbit)

- RV measures M*Sin(i) not mass of the planet. If we discover 3 planets with M*sin(i)= 4, 7, 3 Mearth, we don't really know any of them are Earth-like because we don't know sin(i).

RV Bias from Stellar Magnetic Activity
(11 yr sunspot cycle, on other G stars)

The HARPS search for southern extra-solar planets. ⋆ ⋆⋆

XXX. Planetary systems around stars with solar-like magnetic cycles and short-term activity variation

Dumusque et al.: Planetary systems around stars with activity variation

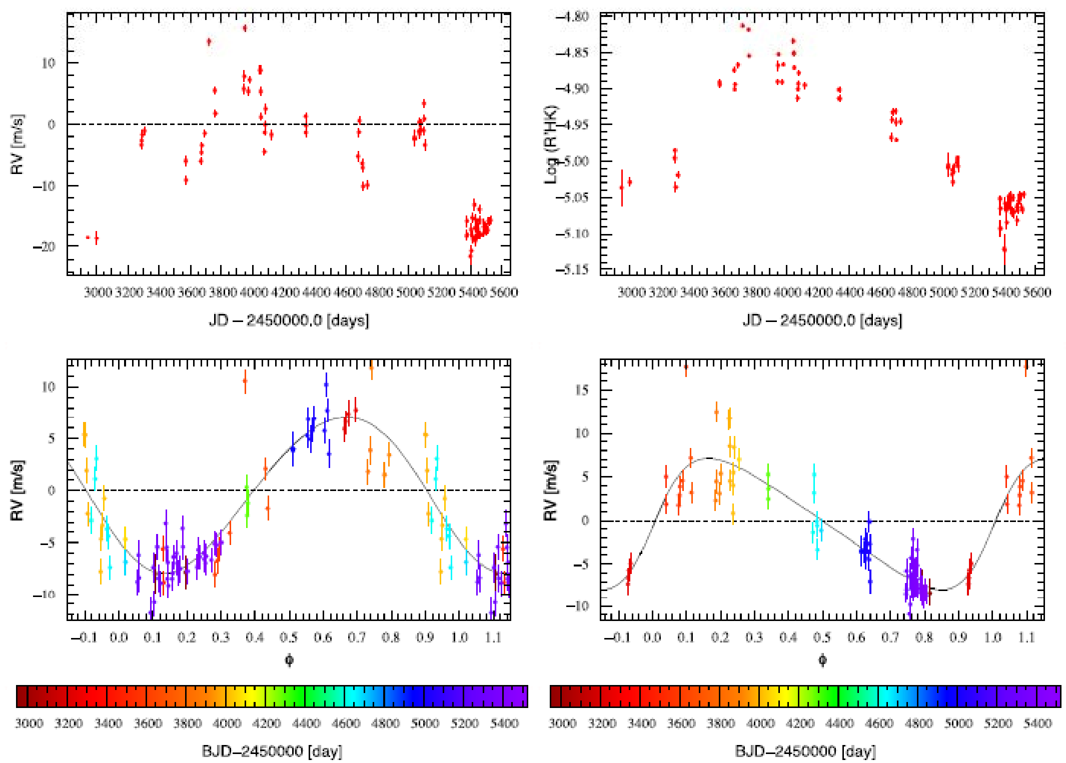


Fig. 1. All the graphs are for HD7199. *Top panel:* RVs and activity index, log(R'_{HK}), as a function of time. *Lower panel:* RVs folded in phase for the two Keplerian fitted. On the left the real planet and on the right the RV variation induced by the magnetic cycle, which is similar to the activity index variation. Thus, we see clearly that magnetic cycles induce a RV variation.

Magnetic cycles on solar like stars can produce RV variations of ~15m/s p-v. These variations can mimic RV signatures of planets. HD7199 is an example of a planet that was discovered, then **"Undiscovered"**.

The HK magnetic activity index is an approximate indicator of RV bias from magnetic activity.

Vertical flow of gas causes a doppler shift but no astrometric error.