Astrometry

- Deals with (precise) positions, angular proper motions, and parallaxes of celestial sources
- Could be *wide-angle* (e.g., for reference systems) or *narrow-angle* (e.g., precision parallaxes, stellar wobbles, etc.)
- Reference coordinate systems (typically equatorial) are defined by a grid of stellar positions; the basic one is the International Celestial Reference System (ICRS), as embodied by the Fifth Fundamental Catalogue (FK5)
- The *Gaia* mission will transform this field
The Evolution of Astrometric Accuracy

- Hipparchus - 1000 stars
- The Landgrave of Hessen - 1000
- Tycho Brahe - 1000
- Flamsteed - 4000
- Argelander - 26000
- PPM - 400 000
- FK5 - 1500
- UCAC2 - 58 million
- Tycho - 1 million
- USNO - 100
- Hipparcos - 120 000
- Gaia - 1000 million

Year

Errors of best star positions and parallaxes
## Some Astrometric Catalogs

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Nstars</th>
<th>$\sigma(p)$ (mas)</th>
<th>$\sigma pm$ (mas/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAO</td>
<td>1966</td>
<td>260 000</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>ACRS</td>
<td>1991</td>
<td>320 000</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>PPM</td>
<td>1991</td>
<td>469 000</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>HIPPARCOS</td>
<td>1997</td>
<td>120 000</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Tycho1</td>
<td>1997</td>
<td>1 060 000</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>ACT</td>
<td>1997</td>
<td>989 000</td>
<td>40</td>
<td>~ 2.5</td>
</tr>
<tr>
<td>TYCHO–2</td>
<td>1999</td>
<td>2 500 000</td>
<td>25</td>
<td>~ 2.5</td>
</tr>
<tr>
<td>UCAC–2</td>
<td>2003</td>
<td>48 330 000</td>
<td>22~70</td>
<td>1~6</td>
</tr>
</tbody>
</table>
Distances and Parallaxes

• Distances are necessary in order to convert apparent, measured quantities into absolute, physical ones (e.g., luminosity, size, mass...)

• Stellar parallax is the only direct way of measuring distances in astronomy! Nearly everything else provides relative distances and requires a basic calibration

• Small-angle formula applies:
  \[ D [\text{pc}] = \frac{1}{\pi} [\text{arcsec}] \]

• Limited by the available astrometric accuracy (~ 1 mas, i.e., \( D < 1 \text{ kpc} \) or so, now)
How Far Can We Measure Parallaxes?

Since nearest stars are > 1 pc away, and ground-based Telescopes have a resolution of ~1 arcsec, might seem impossible to measure \( \pi \) (and thus D) to any useful precision. Actually, it can be done:

1838: Bessel measured \( \pi = 0.316 \) arcsec for star 61 Cyg (modern value \( \pi = 0.29 \) arcsec)

Current ground-based: best errors of ~ 0.001 arcsec

Hipparcos satellite: measured \( \sim 10^5 \) bright stars with errors also of \( \sim 0.001 \) arcsec

GAIA satellite: will measure positions of \( \sim 10^9 \) stars with an accuracy of micro-arcsecs - this is a reasonable fraction of all the stars in the Milky Way!

Currently: measure D accurately to \( \sim \) a few \( \times 100 \) pc
# Parallax Programs

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Date</th>
<th>#stars</th>
<th>(\sigma) (mas)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>YPC</td>
<td>1995</td>
<td>8112</td>
<td>(\pm 15) mas</td>
<td>Cat. of all (\pi) through 1995</td>
</tr>
<tr>
<td>USNO pg</td>
<td>To 1992</td>
<td>(~1000)</td>
<td>(\pm 2.5) mas</td>
<td>Photographic parallaxes</td>
</tr>
<tr>
<td>USNO ccd</td>
<td>From ‘92</td>
<td>(~150)</td>
<td>(\pm 0.5) mas</td>
<td>CCD parallaxes</td>
</tr>
<tr>
<td>Nstars &amp; GB</td>
<td>Current</td>
<td>100?</td>
<td>(\pm 2) mas</td>
<td>Southern (\pi) programs</td>
</tr>
<tr>
<td>Hipparcos</td>
<td>1997</td>
<td>(10^5)</td>
<td>(\pm 1) mas</td>
<td>First modern survey</td>
</tr>
<tr>
<td>HST FGS</td>
<td>1995-2010?</td>
<td>100?</td>
<td>(\pm 0.5) mas</td>
<td>A few important stars</td>
</tr>
<tr>
<td>SIM</td>
<td>2016?</td>
<td>(10^3)</td>
<td>(\pm 4) (\mu)as</td>
<td>Critical targets &amp; exoplanets</td>
</tr>
<tr>
<td>Gaia</td>
<td>2016?</td>
<td>(10^9)</td>
<td>(\pm 10) (\mu)as</td>
<td>“Ultimate” modern survey</td>
</tr>
</tbody>
</table>
Scientific Goals of the GAIA Mission

- >20 globular clusters
- Many thousands of Cepheids and RR Lyrae
- Mass of galaxy from rotation curve at 15 kpc
- 30 open clusters within 500 pc
- Horizon for proper motions accurate to 1 km/s
- Dark matter in disc measured from distances/motions of K giants
- Dynamics of disc, spiral arms, and bulge
- Horizon for distances accurate to 10 per cent
- Proper motions in LMC/SMC individually to 2-3 km/s
- General relativistic light-bending determined to 1 part in $10^5$

1 microarcsec/yr = 300 km/s at z = 0.03 (direct connection to inertial)
Astrometry in Practice

- Typically telescopes do not point better than to a few arcsec; so one points to a nearby star with precisely known coordinates, zeroes the telescope system, and does a small, “blind” offset to a target.

- For imaging observations, one often uses positions of the stars in the frame, which have known positions (usually to a ~ 0.2 arcsec accuracy, e.g., from the USNO-B catalog), measures their XY positions in the image, and solves for the XY ⇔ RA,Dec transformation.

- These transformations can be encoded in the image headers using the World Coordinate System (WCS) standard.

- One-stop shop: http://www.usno.navy.mil/USNO

- Check out also http://Astrometry.net

- For the “real” astrometry, milli-arcsec is the relevant unit.
Galactic Center Astrometry

(Ghez et al., Genzel et al.)