A Random Walk Through Astrometry

Astrometry: The Second Oldest Profession

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Random Topics to be Covered

- Astronomical reference frames
- Units
  - Angles: Arcseconds
  - Brightness: Magnitudes (and star density)
- Moving from the optical into the infrared

Astrometry: What is it? Why do it?

- What:

  The science of measuring the positions and motions of celestial objects and interpreting the results

- Why:
  - Many practical applications, involving navigation (broadly interpreted) and timekeeping
  - Sets the fundamental distance scale of the universe
  - Established the universality of gravitational law
  - Provides information on the evolution of the solar system and galaxy

DoD Uses for Astrometric Data

- Astro-inertial navigation systems
  - ICBM guidance
- Azimuth calibration
- Deflection of the vertical determination
- Satellite attitude control / sensor orientation
- Ground-based satellite tracking, orbit determination
- Near Earth object (NEO) detection
- Standard celestial navigation
- Determining astronomical time and Earth orientation for GPS

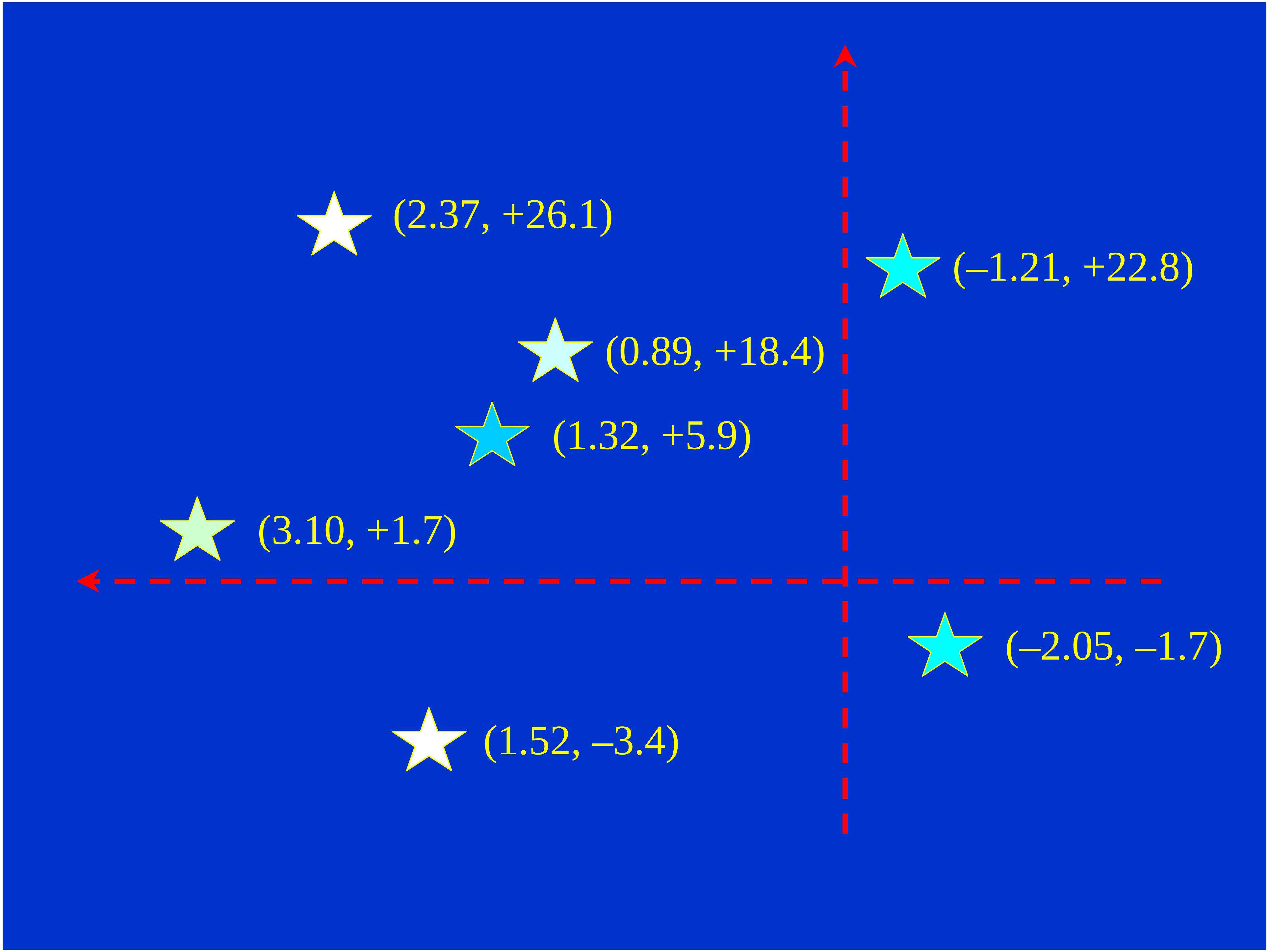

These applications generally involve measuring something against a background of stars. . .
. . . that is, motions of objects are measured within a *celestial reference frame*

What is an Astronomical Reference Frame?

An ensemble of coordinate values (and their rates of change) assigned to specific astronomical objects for a given epoch

For example, the data in a star catalog

This is completely analogous to the establishment of a geodetic reference system using an ensemble of Earth-fixed benchmarks whose coordinates are have been determined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(1.52, –3.4)

Types of Astronomical Reference Frames

- Extragalactic

  Fiducial points are quasars or nuclei of galaxies

  - Constructed from radio λ observations (VLBI)
  - No assumed angular motions — too far away
  - But …radio sources often variable

- Galactic (Stellar)

  Fiducial points are stars

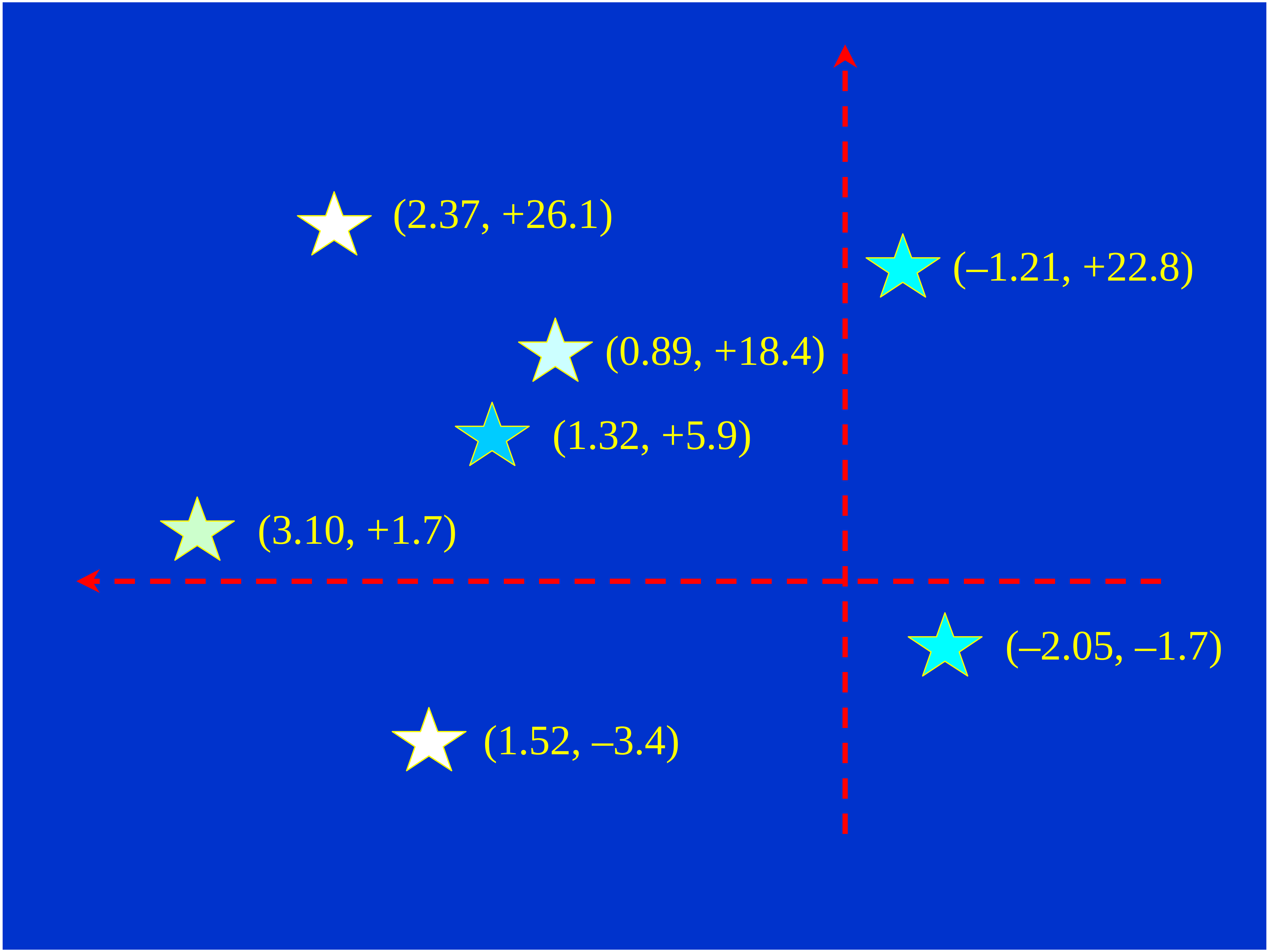
  - Lots of energy
  - Energy in λ bands of practical use
  - But … stars move, sometimes in complex ways

- Dynamical

  Fiducial points are planets or other orbiting bodies in the solar system (natural or artificial)

Complications

- Problem is over-determined: really only need two stars (3 coordinates) to define a reference frame
- Therefore, for N stars in a catalog, ~$N^2/2$ independent reference frame definitions — which will not, in general, be consistent due to errors in coordinate values
- Not a bad problem as long as errors are random
- If errors are a function of position on the sky, the reference frame is warped (systematic distortions)
- Also problematic if errors are a function of magnitude or color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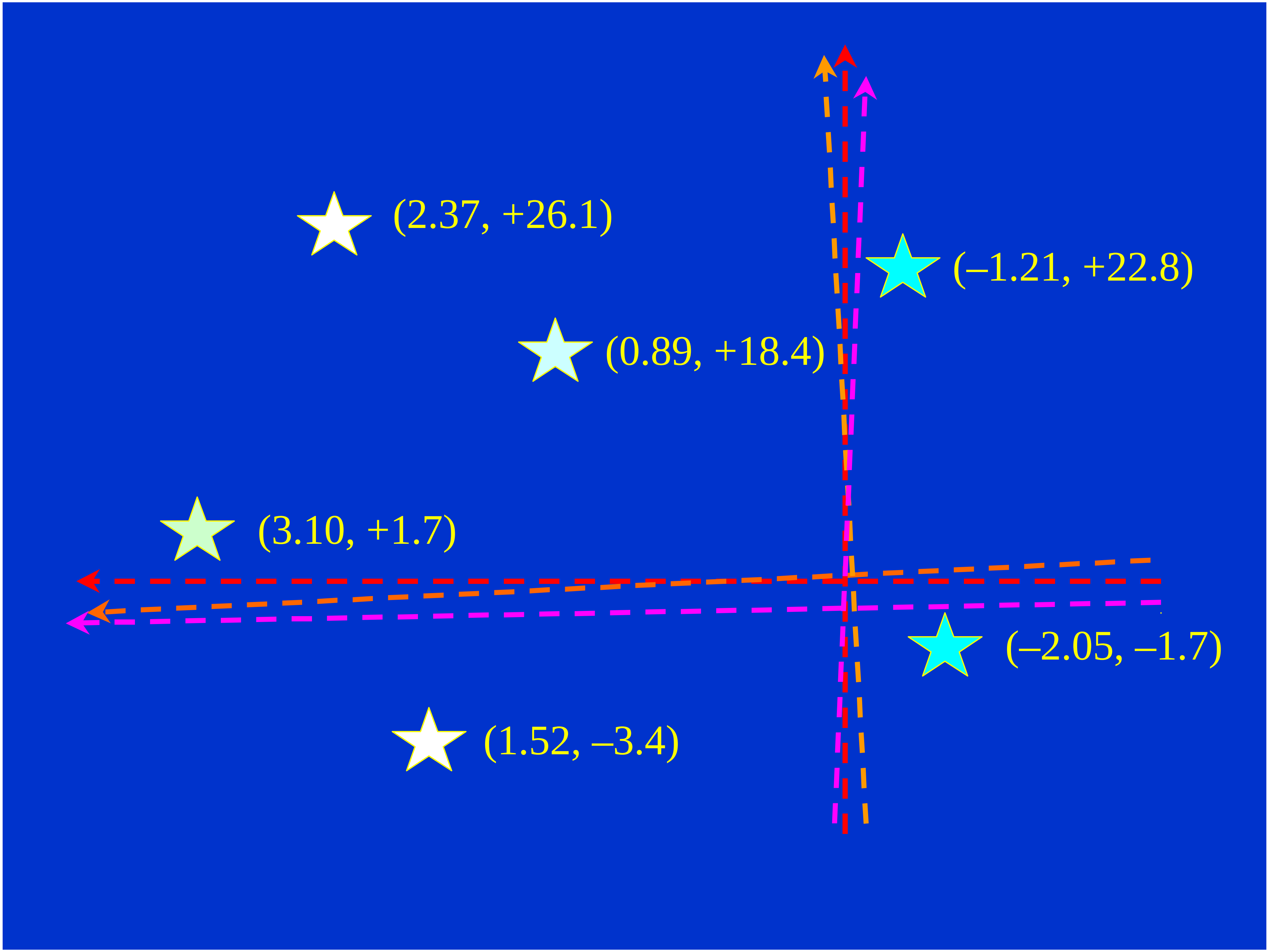
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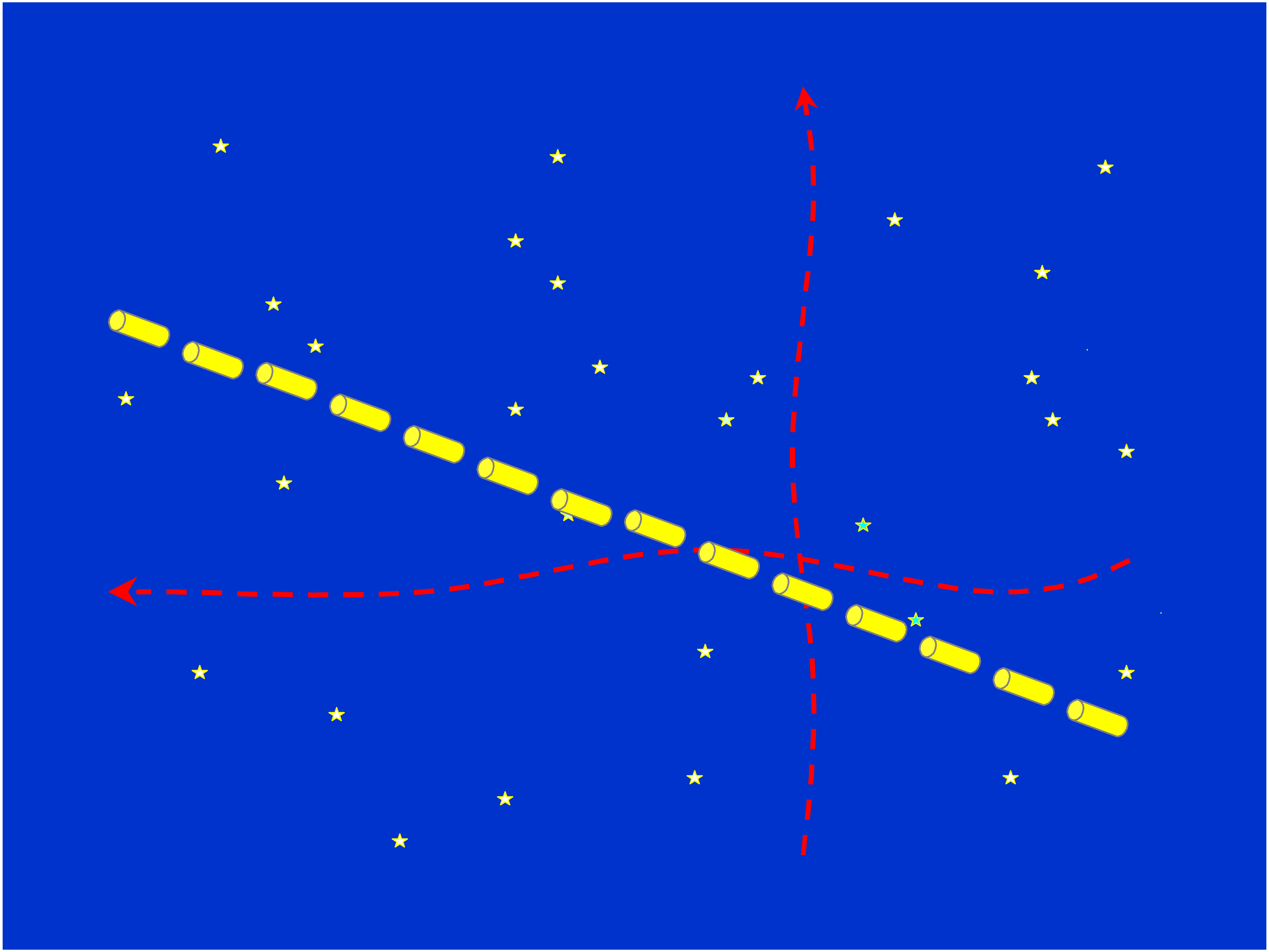
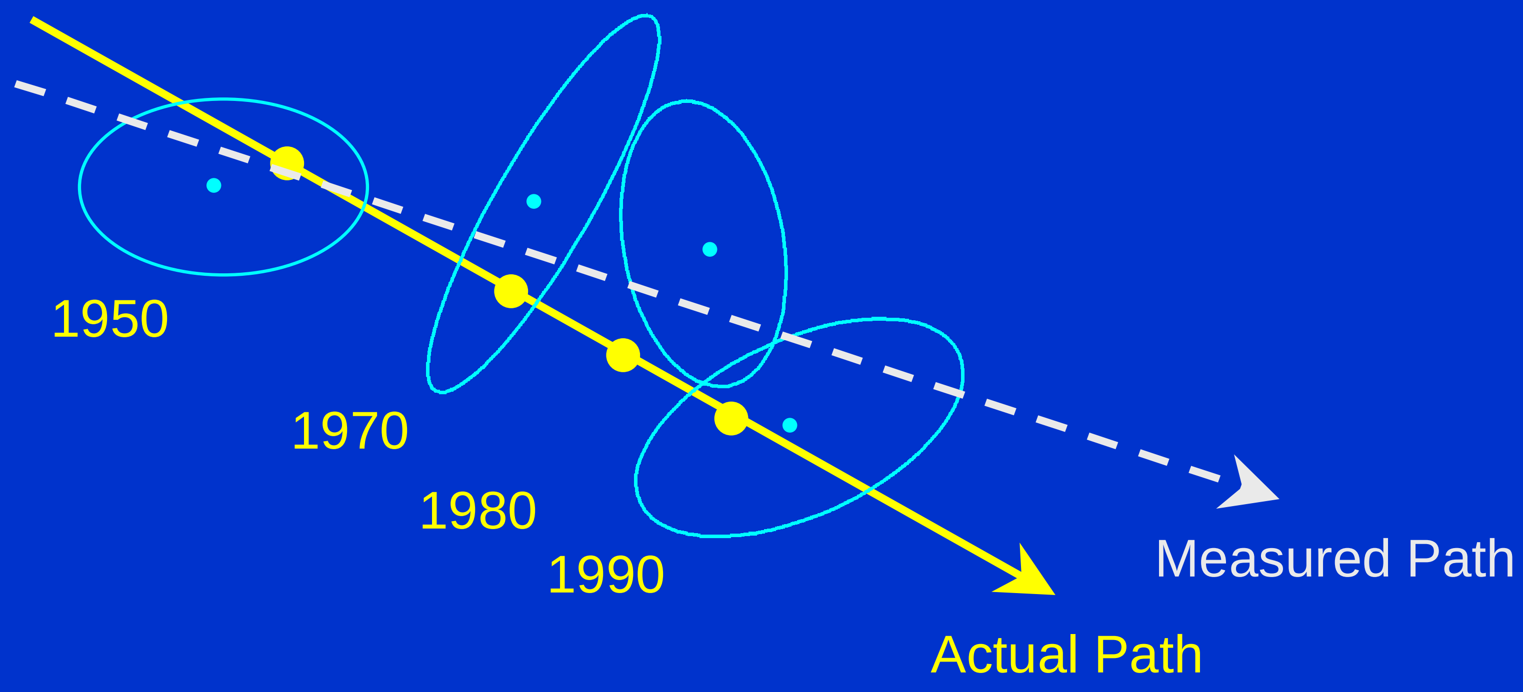


Why star positions, and the reference frames they define, degrade with time




You are here
Stars are part of an inherently non-inertial system!

Desirable Features of Astronomical Reference Frames

- Should define a local *inertial* reference system

  (no rotations)
- Should be *isotropic* (no distortions)
- Should be *accurate*
- Should have a suitable *density* of fiducial points
- Should have fiducial points *detectable* by relevant sensors (sufficient flux in sensor bandpass)

Issues in Constructing Reference Frames

- Stars part of galaxy, inherently a non-inertial system
- Stars often part of binary or multiple systems
  - If resolved, orbital motions of components must be determined
  - If unresolved, photocenter may move or be $f(\lambda)$
- Parallax (distance) of stars must be determined
- Quasars and AGNs have time-variable flux and structure
- Aligning reference frames from different λ regimes difficult — objects bright in one regime faint in the other

Units! The Secret Code

- Arcseconds
- Magnitudes

Angular Units: Arcseconds

Application:	Surface Nav	LEO	Geosync
Distance:	1 $R_\oplus$	500 km	35k km
Angle			
1 arcsec = 4.8 μrad	31 m	2.4 m	170 m
0.1 arcsec = 0.48 μrad	3.1 m	24 cm	17 m
1 mas = 4.8 nrad	3.1 cm	2.4 mm	17 cm
1 μas = 4.8 prad	31 μm	2.4 μm	0.17 mm

The Magnitude Scale

- Goes back to Hipparcus (~150 BC), who divided naked eye stars into 6 categories of brightness

  1 to 6, from brightest to faintest

- Quantified in the 19th century:

  5 magnitudes = factor of 100 in brightness

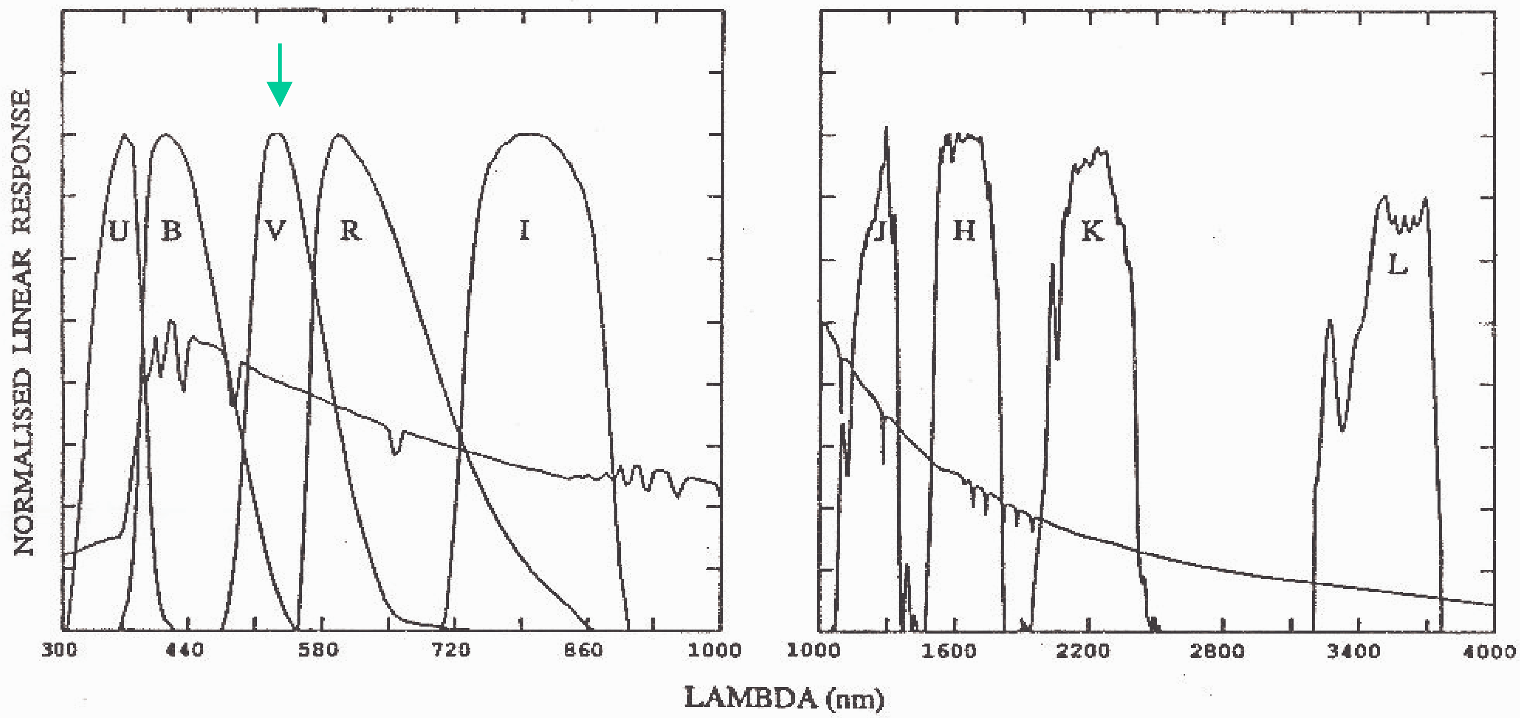
  $\Rightarrow$ 1 magnitude = factor of 2.512 in brightness

- Now calibrated to absolute measures of energy received within a given wavelength band:

  U, V, B, R, I, J, H, K, L, u, v, b, y, etc.

- Most common band V = m_V = visual magnitude

UBVRIJHKL Photometric Bands



The passbands of the *UBVRIJHKL* system, plotted as functions of the wavelength in nm.

from *The Astronomy and Astrophysics Encyclopedia*, ed. S. P. Maran (1992)

Scale of Visual Magnitude

–4	Venus
–1.5	Sirius
0 to 6	most naked-eye stars
5	Andromeda galaxy
~8	magnitude at which there is 1 star / degree^2
9-10	faintest stars in binoculars
12	faintest stars in small (3-inch) telescope
12	brightest quasar (most are 15 and fainter)
14	Pluto
19.5	Palomar Sky Survey V limit (Palomar QV, 1980s)
~24	old photo plate limit with 200" telescope
29	current limit?

Density of Astronomical Objects on the Sky

- The volume of space enclosed by a radius d goes up as d^3
- The apparent brightness L of an object at distance d falls off as d^2

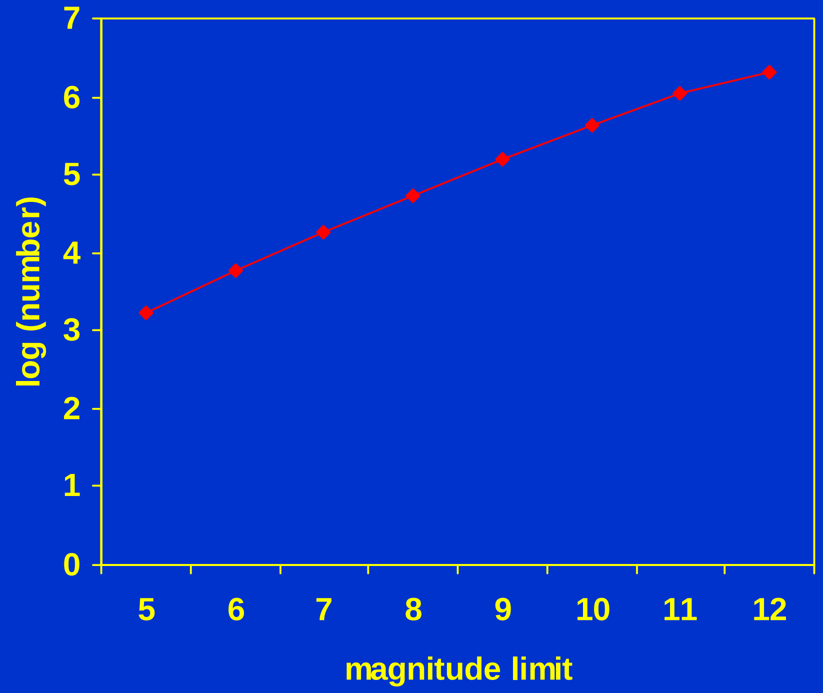
$\Rightarrow$ The total number of objects brighter than apparent brightness L is proportional to $L^{-3/2}$

$\Rightarrow$ The total number of objects brighter than magnitude m is 3.98 times the number brighter than m–1

Star Numbers vs. Magnitude

Star Counts from Tycho-2

m_v limit	no. stars	
5.0	1,658	
		3.44
6.0	5,713	
		3.18
7.0	18,183	
		2.98
8.0	54,192	
		2.85
9.0	154,656	
		2.70
10.0	417,769	
		2.59
11.0	1,083,253	
		1.99
12.0	2,158,589	



Data courtesy Rob Olling

Moving from the Optical into the Infrared (IR)

- Why do it?
- Issues

Moving into the IR — Why?

- Provides sensitivity to objects cooler than the surface of the Sun (~5800K). For example, peak radiation at:

  0.7 μm for 4000K 1 μm for 2900K

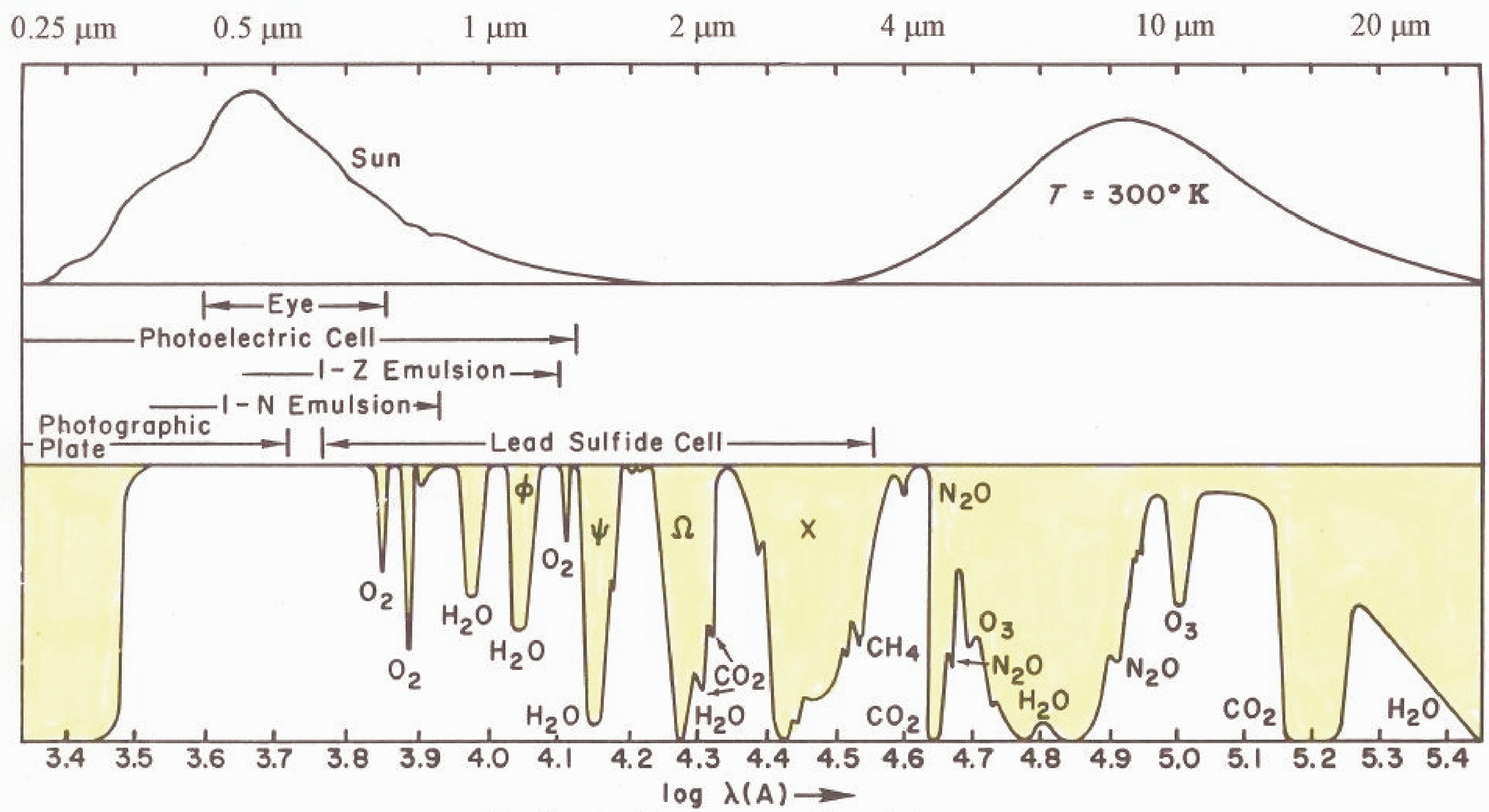
  1.5 μm for 1900K 10 μm for 300K

- For astronomy, provides info on cool stars, brown dwarfs, “hot Jupiters”, star formation, interstellar dust, and highly redshifted galaxies
- For DoD applications, provides sensitivity to rocket plumes, detonations of various kinds, and, at very long λ (~10 μm), to ordinary objects in equilibrium with ambient sunlight

Moving into the IR — Why Not?

- Detectors less well developed — can't use CCDs (silicon) beyond above 1.1 μm
- Less resolution for given aperture size
- Atmosphere opaque to IR except in certain windows
  - Observations best from space
- Bright background:
  - 1-2.5 μm atmospheric emissivity, mainly due to OH
  - >2.5 μm emissivity of everything else — telescope, optics

Atmospheric Transmittance



THE OPTICAL WINDOW IN THE EARTH'S ATMOSPHERE

from *Astrophysics: The Atmospheres of the Sun and Stars*, L. H. Aller (1963)

Catalog Issues

- More stars!
  - Interstellar absorption less as λ increases — see more stars
  - Galaxy contains more cool stars than hot
- Can use optical data for stars in near IR, but …
  - Extrapolating IR magnitudes from visual very tricky
  - Completeness in visual to a certain magnitude in no way implies completeness in IR to similar magnitude
- At magnitudes > 20, see many more galaxies

  very distant ones redshifted into the IR