6 Photometric Systems & Astronomy with CCDs

6.1 Vega vs. AB magnitudes

Earlier, we have introduced magnitudes as logarithmic units that express relative brightnesses. Yet, the apparent magnitude of the Sun in the V filter is understood to be -26.76 ± 0.02 mag and the surface brightness in mag arcsec^{-2} in a galaxy was plotted as a function of radius as if they were physical units on some absolute scale. So how did we get from what is inherently an ambiguous relative unit to a unit with an absolute physical meaning?

According to the definition of *magnitude*, we have:

$$m_1 - m_2 \;\equiv\; -2.5\,\log\frac{f_1}{f_2} \;=\; -2.5\,\log f_1 \;+\; 2.5\,\log f_2 \tag{1}$$

If m_2 were the magnitude that corresponds to a known flux density f_2 in physical units of ergs s^{-1} cm^{-2} Å^{-1} (in the case of f_λ) or of ergs s^{-1} cm^{-2} Hz^{-1} (for f_ν) — in particular if $m_2 \equiv 0$ for that known flux density —, then the term $2.5\,\log f_2$ becomes equivalent to an absolute *zeropoint* (zp) for the magnitude scale:

$$m_1 = -2.5\,\log f_1 + zp \tag{2}$$

6.1.1 Vega magnitudes

The ultimate standard and reference for all classical broad-band photometry is the star α Lyrae (i.e., Vega). By substituting the flux density in a given filter of Vega for f_2 in Eq. (1) and dropping the subscripts "1", we obtain:

$$m - m_{\rm Vega} = -2.5\,\log f_\lambda \;+\; 2.5\,\log f_{\lambda,\rm Vega}$$

However, this would still leave us with $m_{\rm Vega}$. The final step, then, to yield a usable physical scale is to set:

$$m_{\rm Vega} \equiv 0 \quad \text{in all filters } \textbf{\textit{per definition}} \quad \Rightarrow m - m_{\rm Vega} \;\equiv\; m$$

Hence:

$$m \;=\; -2.5\,\log f_\lambda \;+\; 2.5\,\log f_{\lambda,\rm Vega} \tag{3}$$

where the last term is the zeropoint, $zp(\lambda)$, on the Vega magnitude system. For a flux density outside the Earth's atmosphere of $(3.59 \pm 0.08) \times 10^{-9}$ ergs s^{-1} cm^{-2} Å^{-1} at 5480Å, this zeropoint $zp(5480\text{Å}) = -21.112$.

As a corollary of the requirement that $m = 0$ at all wavelengths, the *color* of Vega in any pair of filters is 0, as well.

Fig. 1(a) shows the spectrum of Vega as a function of wavelength. Note, that the flux density of Vega varies greatly over the UV–near-IR regime, yet the magnitude corresponding to that flux density is equal to 0 at every wavelength.

Since it is impractical for every observer to observe Vega, a reference set of several dozens of, generally fainter, secondary standard stars was observed. During WW II, Johnson made extensive photo-electric observations, spanning many years, through standard apertures in his UBV filter system. The UBV filter system was the first known standardized photometric system. The filter set was later extended toward the near- and mid-IR with $RIJK$ and L filters.

As progressively more precise magnitude and color measurements of an increasingly large number of stars, sampling a large range in colors, were placed onto the standard system of Johnson, slight inconsistencies in magnitude and colors became apparent. To remain as consistent as possible with earlier work, the V magnitude of Vega had to be adjusted slightly upward from exactly zero. The current best estimate is $m_V = +0.035 \pm 0.012$ mag for $f_{\lambda,V} = (3.593 \pm 0.084) \times 10^{-9}\,\mathrm{ergs\,s^{-1}\,cm^{-2}\,Å^{-1}}$ (Colina & Bohlin 1994).

More recently, Landolt (1992) published photo-electric $UBVR_cI_c$ photometry of a large number of equatorial (Dec $\sim 0°$) fields in which stars of very different colors are relatively close together on the sky (within $\sim$5′–15′ on the sky). The transformations of his photometry onto the original system, again meant very slight changes to the original system. When using Landolt standard stars to photometrically calibrate you CCD images, you are actually calibrating onto Landolt's system, and not quite the original Vega system of Johnson.

Even more recently, Stetson (2000) published a very large database of BVR_cI_c standard stellar magnitudes within the Landolt equatorial fields and in many other common fields across the sky based on (largely archival) CCD observations. His photometry is reduced onto the Landolt system, but his measurement method differed. Whereas Landolt used fixed circular apertures of 14″ with his photomultiplier tube, and hence often also measured the flux of adjacent fainters stars within that aperture, Stetson used the technique of PSF fitting, where each star is measured seperately.

▷ *When calibrating CCD images, care needs to be taken to reproduce as close as possible the measurement method employed to obtain the original standard star photometry.*

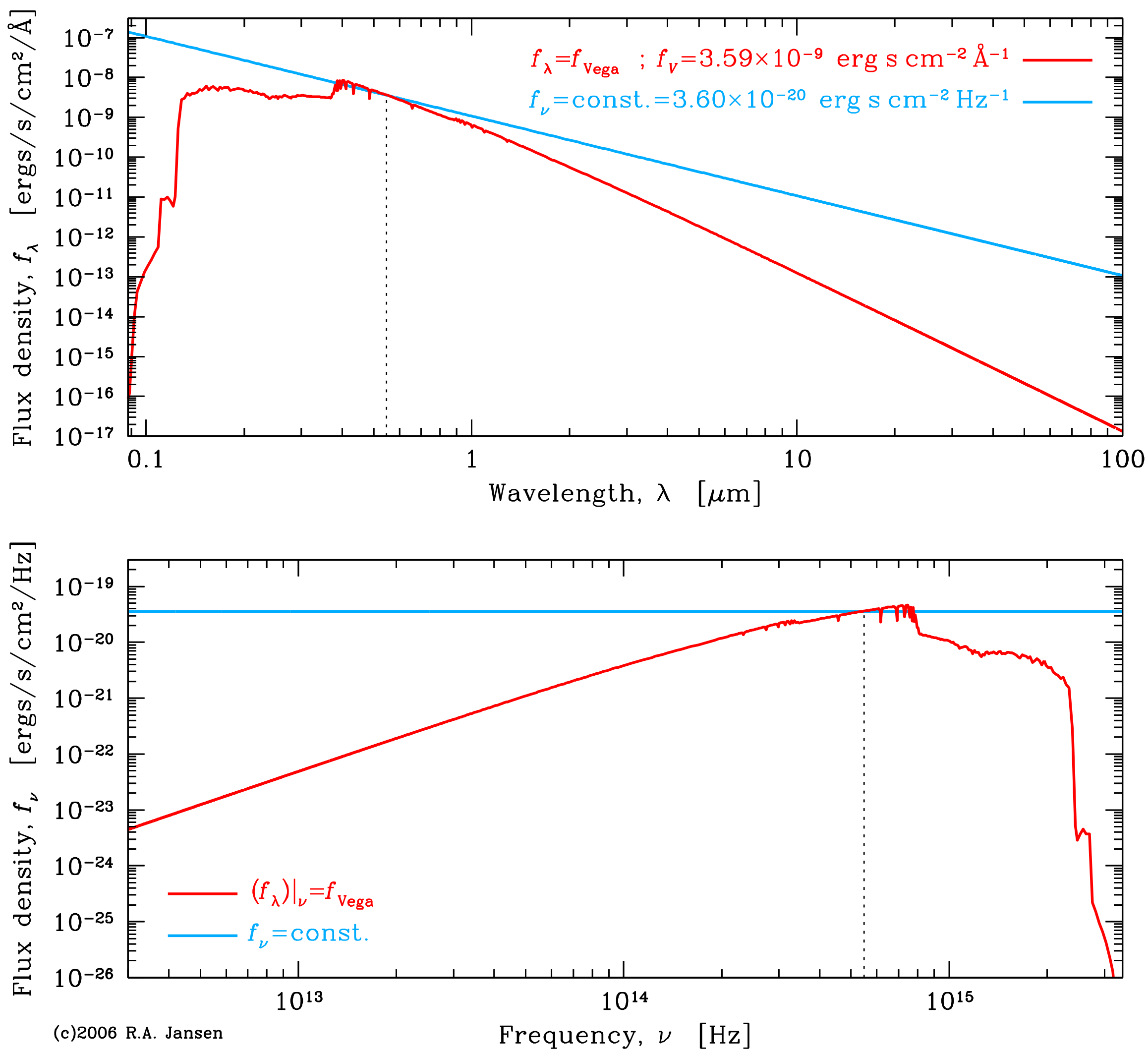

Figure 1: Comparison of the spectrum of α Lyrae (Vega) and a spectrum that is flat in f_ν. In the top panel, both are plotted as f_λ (in ergs s^{-1} cm^{-2} Å^{-1}) versus wavelength λ (in μm), while in the bottom panel they are presented as f_ν (in ergs s^{-1} cm^{-2} Hz^{-1}) versus frequency ν (in Hz). Both spectra are equal at the effective wavelength of the V filter, at 5480Å. The mid- to far-IR portion of the spectrum of Vega was replaced by the stellar atmospheric model of Kurucz (1979): an actual IR spectrum of Vega would show a significant additional, non-photospheric component due to its circum-stellar debris disk.

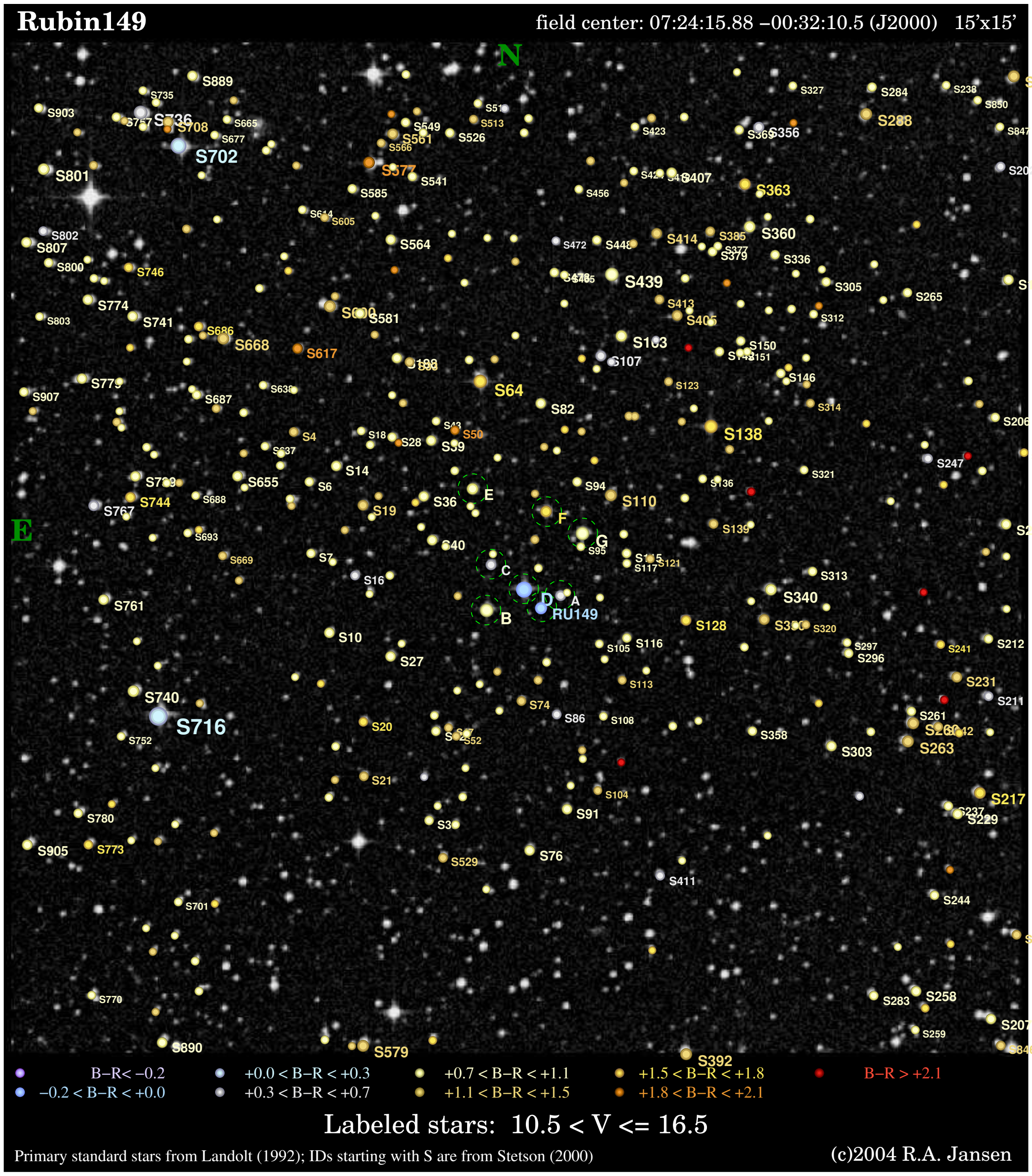

Figure 2: In standard field Rubin 149, Landolt (1992) published $UBVRI$ filter photoelectric photometry of the 8 stars labeled "Ru149" and A through G. The circular apertures used with his photomultiplier tube had a diameter of 14″. Since this field is densely populated with stars, such apertures also included neighboring stars. To use Landolt's magnitudes, one has to measure the total signal within synthetic apertures of the same diameter. Stetson (2000) published standard star photometry for all labeled stars in the larger general field of the Rubin 149 asterism. His measurements include many fainter stars that are observable even with large aperture telescopes. His measurements are reduced onto the Landolt system, but his measurement method differed. Because he fitted the stellar PSF, his published magnitudes do *not* include signal from neighboring stars. To use Stetson's photometry, one has to reproduce the same method (see also Bessell 2005).

6.1.2 AB magnitudes

To avoid the problems with Vega magnitudes — that the flux density that corresponds to $m = 0$ differs at every wavelength, and that the flux of Vega can become exceedingly small at wavelengths outside the UV–near-IR regime[1] —, another magnitude system, the *AB* or *spectroscopic* or *natural magnitude system*, was deviced (Oke & Gunn 1983). In the AB magnitude system, the reference spectrum is *a flat spectrum in* f_ν:

$$f_\nu \;\equiv\; \text{const.} \quad [\mathrm{ergs\,s^{-1}\,cm^{-2}\,Hz^{-1}}].$$

That constant is per definition such that in the V filter: $m_V^{Vega} \equiv m_V^{AB} \equiv 0$ (or more accurately: $f_\nu\,\mathrm{d}\nu \equiv f_\lambda\,\mathrm{d}\lambda$ when averaged over the V filter, or at the effective wavelength of the V filter, $\lambda_{\rm eff} = 5480$Å.

▷ *Note that the AB magnitude system is expressed in* f_ν *rather than* f_λ!

The flux density in f_ν is related to the flux density in f_λ by:

$$f_\nu\ [\mathrm{ergs\,s^{-1}\,cm^{-2}\,Hz^{-1}}] \;=\; \frac{\lambda^2}{c}\cdot 10^8 \cdot f_\lambda\ \ [\mathrm{ergs\,s^{-1}\,cm^{-2}\,\text{Å}^{-1}}]$$

where we used $\lambda\,\nu \equiv c$ and transformed from $f_\lambda\,\mathrm{d}\lambda$ to $f_\nu\,\mathrm{d}\nu$. The factor 10^8 is included, because the natural units of wavelength are cm, not Å. Converting the Vega magnitude zeropoint gives:

$$m \;=\; -2.5\,\log f_\nu \;-\; (48.585 \pm 0.005) \qquad (4)$$

where the exact value of the zeropoint depends somewhat on the literature source (e.g., Hayes & Latham 1975; Bessell 1988,1990), based on a magnitude at 5556Å for Vega of 0.035–0.048 mag and a corresponding flux density of $(3.56\text{–}3.52)\times 10^{-20}$ ergs s^{-1} cm^{-2} Å^{-1} .

The AB magnitude system is also called the spectroscopic magnitude system, because with its constant zeropoint, it is useable at any wavelength in bandpasses of any width, and hence, also for narrow-band imaging and spectroscopy. In ground-based broad-band imaging, however, the Vega magnitude system is still the most common system. Unless explicitly noted otherwise, one should assume Vega magnitudes.

[1] and not even due to the stellar atmosphere in the mid-IR–far-IR: there one actually detects the circumstellar debris ring!

6.2 Filters, filters and yet more filters

- Johnson-Morgan/"Johnson" — U, B, V, R, I broad-band filters; extended to the near-IR with J, K, and L. The main disadvantage of the U filter was that it's blue cut-off was mainly determined by the transparency of the atmosphere (rather than by the glass of the filter).

- Kron-Cousins/"Cousins" — R_c, I_c broad-band filters; better behaved in their red-tail, better positioning in wavelength with respect to UBV.

- Bessell (1979,1990), Bessell & Brett (1988)/"Bessell" — better characterization and formalization of what the $UBVR_cRI_cIJHKLM$ broad-band bandpass curves (resulting from filter plus detector) *should* look like.

- Strömgren filters — u, b, v and y; medium-band filters, specifically designed for stellar astrophysics (hot vs. cool stars): u and b straddle the Balmer break (actually the Ca II H+K break at ∼4000Å), and $u-b$ and $v-y$ colors provide the strength of that break and the continuum slope redward of the Balmer break.

- Defined by G. Wallerstein; developed by Canterna (1976); on Geisler (1996) system of CCD standards; see also Bessell (2001)/ "Washington system" — C, M, T_1 and T_2, specifically designed for metallicity studies in old stellar populations.

- Straižys et al. (1966); Straižys & Zdanavičius (1970)/"Vilnius system" — U, P, X, Y, Z, V, and S. Mainly used for stellar classification.

- Gunn, Thuan & Gunn / "Gunn" — u, g, r (later also i, z), have filters with transmission curves with steeper cut-on and cutt-off; the precursor of the Sloan and various *HST* filters.

- 2MASS filters; Jarret et al./"2MASS system" — J, H, K_s; by reducing the effective wavelength of the K filter from 2.2 to 2.15 μm and designing a steeper red cut-off, the sky background in K_s is significantly darker than in the Johnson K filter.

- Sloan Digital Sky Survey/"Sloan" — u', g', r', i', and z'. Square filter transmission curves with minimal overlap and minimal gaps between the filters. Optimal broad-band filter set for photometric redshifts and quasar searches.

- Beijing-Arizona-Taiwan-Connecticut filter set; spectro-photometrically calibrated by Yan (2000)/"BATC" — System of 16 medium-band filters in near-UV through near-IR that avoid night-sky emission lines. Optimal medium-band filter set for photometric redshifts and (high-redshift) emission-line object searches.

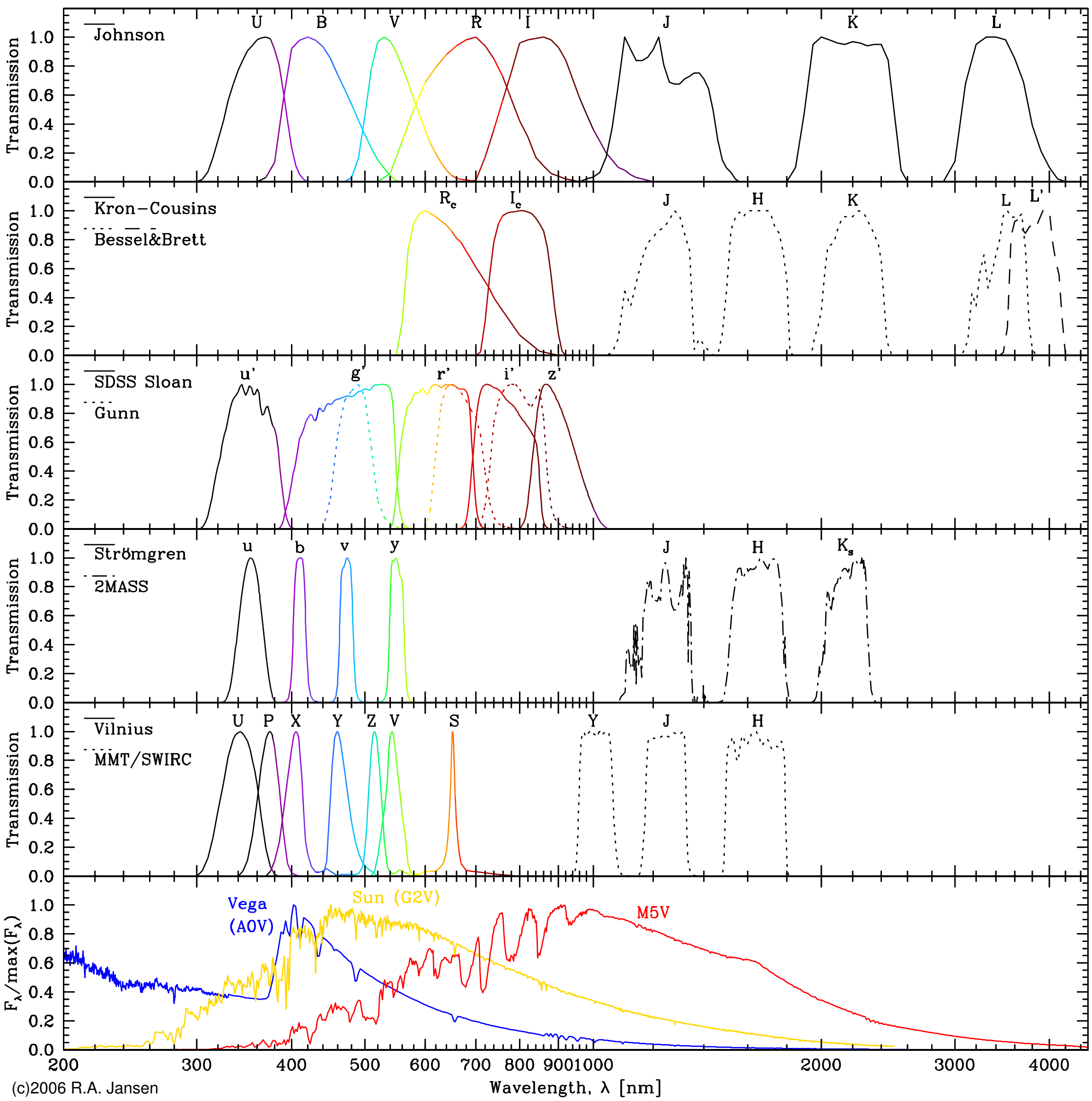

Figure 3: Overview of various filter sets (as labeled) and comparison with the spectra of an A0V (Vega), G2V (Sun) and M5V star.

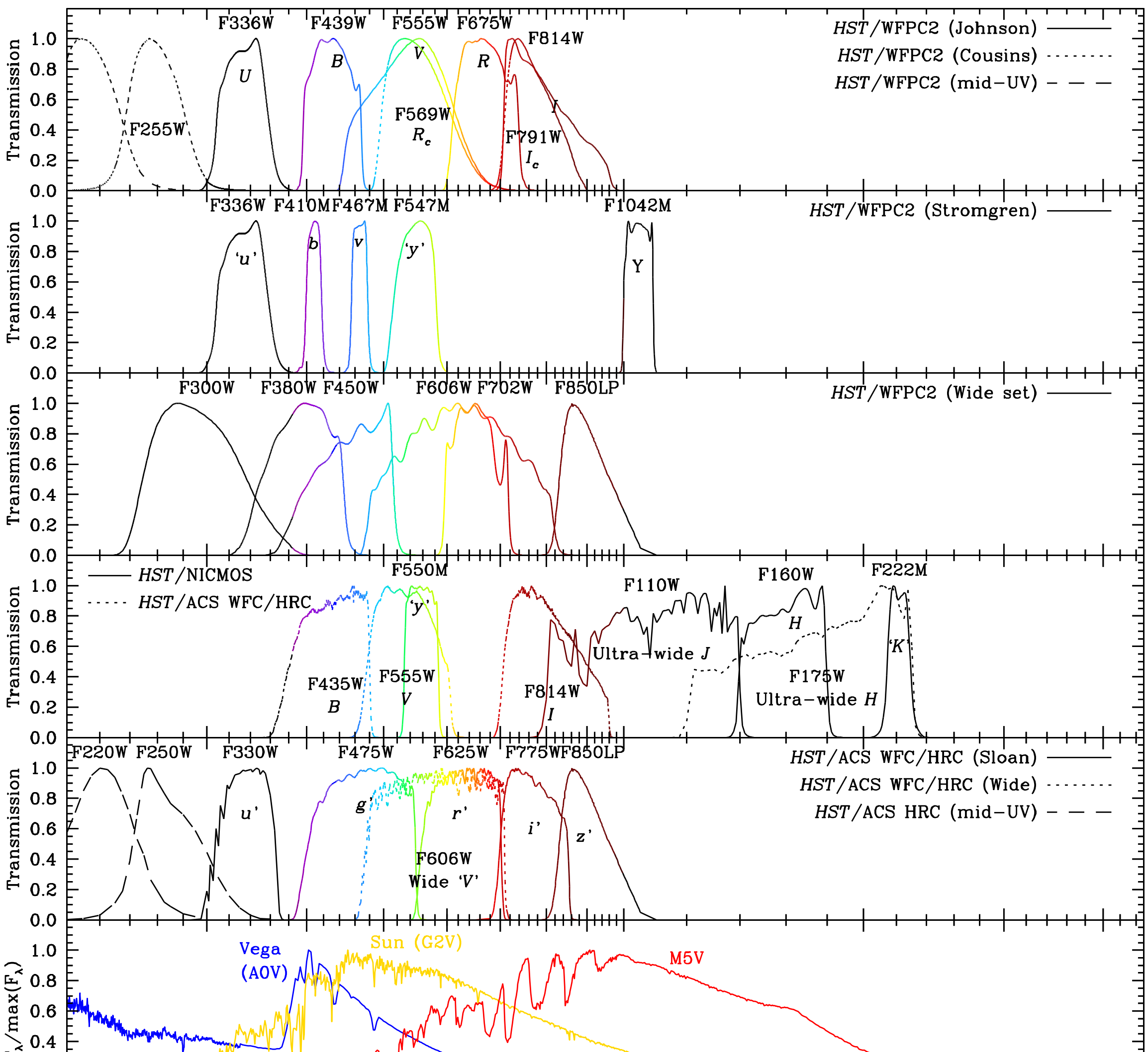

Figure 3: [*Continued*] Overview of various filter sets (as labeled).

7 Types of astronomical observations with CCDs

- *Imaging* — faithfully (in some way) record the spatial (angular) distribution of brightness on the sky
- *Astrometry* — faithfully record the relative or absolute positions of sources on the sky (regardless of brightness)
- *Photometry* — faithfully record the relative or absolute brightness of sources on the sky (regardless of position and possibly regardless of how flux is distributed on the sky)
- *Spectroscopy* — faithfully record the relative or absolute flux density as a function of wavelength or frequency
- *Kinematics* — faithfully record the relative or absolute velocities of objects or parts thereof with respect to a suitable standard of rest
- *Polarimetry* — faithfully record (relative) polarizations (degree and linear/circular)
- *Interferometry* — faithfully record (relative) phases or phase distributions of one or more sources.
- *Photon timing* — faithfully record (relative) arrival times of photons from one or more sources.
- mixtures of any of the above, e.g., *surface photometry*, *spectrophotometry*, *integral field spectroscopy*, *combining both astrometry and photometry*, etc...

For imaging, one has to consider the *plate scale* and *geometric distortions* (the latter particularly for off-axis instruments, but depending on the telescope- and instrument-design, even on-axis instruments may show significant geometric distortions.

For photometry, one has to consider *detection* vs. *measurement* (cf. imaging), *aperture* photometry, *curve of growth* total photometry, *PSF fitting*, or *differential* photometry. Calibration onto an absolute flux system (*AB magnitudes*) or relative system (e.g., with respect to α Lyrae (Vega)).

Appendix A. Sources, references, and additional reading

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ESO's CCD Performance and Results web-page (*http://www.eso.org/projects/odt/Publications/-CCDpub_99/public.html*)

Molecular Expressions' Optical Microscopy Primer, *Digital Imaging in Optical Microscopy* (*http://micro.magnet.fsu.edu/primer/digitalimaging/*)

Nikon's Microscopy U, *"Introduction to Charge-Coupled Devices"*, by: K.R. Spring, T.J. Fellers & M.W. Davidson (*http://www.microscopyu.com/articles/digitalimaging/ccdintro.html*)

SITe 2048×4096 Scientific-Grade CCD (ST-002A CCD data sheet) (*http://www.ociw.edu/-instrumentation/ccd/parts/ST-002A.pdf*)

Outreach and Education site of the Australia Telescope (*http://outreach.atnf.csiro.au/education/-senior/astrophysics/*)

Frank Lakiere's web-site on photography (*webhost.ua.ac.be/elmc/website_FL/index-eng.htm*)

Various *Wikipedia* pages (beware: information in these may neither be complete nor correct)