Equivalent contrast of CCD read noise for the AFTA coronagraph

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Beginning with the Johnson-Cousins V-band zero point:

$f_\lambda = 3.63 \times 10^{-9} \frac{\text{ergs}}{\text{s}\cdot\text{cm}^2\cdot\text{Å}} = 3.63 \times 10^{-8} \frac{\text{J}}{\text{s}\cdot\text{m}^2\cdot\mu\text{m}}$, from Table A2 in Bessell et al. (1998).

The energy per photon at $\lambda = 0.55\ \mu$m:

$$\begin{aligned} E_\lambda &= hc/\lambda = 6.626 \times 10^{-34}\text{J}\cdot\text{s} \times 3 \times 10^{8}\text{ms}^{-1}/0.55 \times 10^{-6}\text{m} \\ &= 3.61 \times 10^{-19}\ \text{J}\cdot\text{phot}^{-1} \end{aligned}$$

Since the apparent magnitude of a star is $m_V = M_V + 5\log_{10}(d/\text{pc}) - 5$, and the absolute magnitude of the Sun $M_V = 4.83$, the photon flux from a twin Sun at $d = 10$ parsec over a 10% bandwidth centered at 0.55 μm is

$$\begin{aligned} \Phi_\star &= f_\lambda \Delta\lambda / E_\lambda \cdot 10^{-m_V/2.5} \\ &= 3.63 \times 10^{-8} \frac{\text{J}}{\text{s}\cdot\text{m}^2\cdot\mu\text{m}} \cdot 0.055\mu\text{m} \Big/ \left(3.61 \times 10^{-19}\text{J}\cdot\text{phot}^{-1}\right) \cdot 10^{-4.83/2.5} \\ &= 5.5 \times 10^{9}\ \text{phot}\cdot\text{s}^{-1}\text{m}^{-2} \cdot 10^{-4.83/2.5} \\ &= 6.46 \times 10^{7}\ \text{phot}\cdot\text{s}^{-1}\text{m}^{-2} \end{aligned}$$

Note this is slightly lower than the value that would be found using Bijan Nemati's spreadsheet, mainly because I use a 50 nm (10%) bandwidth rather than a 89 nm one, and my V-band zero point disagrees slightly.

An expression for the photoelectron count rate from the star, when it is off-axis from the coronagraph is

$$n_\star = \Phi_\star A_{\text{eff}} \eta T_{\text{PSF}} Q$$

where A_{eff} is the effective area of the telescope after the secondary obstruction, η is the reflective loss factor, T_{PSF} is the fraction of non-scattered starlight incident on the primary mirror contained in the core of the off-axis coronagraphic PSF, and Q is the quantum efficiency. I take nominal values for these from Nemati's spreadsheet: $A_{\text{eff}} = 4.117\ \text{m}^2$, $\eta = 0.97^{15}$, $T_{\text{PSF}} = 0.05$, and $Q = 0.8\ \text{e}^-/\text{phot}$. With these values I find

$$\begin{aligned} n_\star &= 6.46 \times 10^{7}\ \text{phot}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot 4.117\ \text{m}^2 \cdot 0.97^{15} \cdot 0.05 \cdot 0.8\ \text{e}^-/\text{phot} \\ &= 6.74 \times 10^{6}\ \text{e}^-/\text{s}. \end{aligned}$$

Say we need M exposures of duration τ to reach a required planet detection confidence, using R CCD pixels at the core of the planet PSF (the same off-axis coronagraph PSF considered above, but now at the much lower amplitude of the hypothetical planet). If we symbolize the read noise in each CCD pixel by σ_r, then the total read noise of all the included pixels of all the exposures, summed in quadrature is

$$\sigma_{r,M,R} = \sqrt{MR\sigma_r^2}.$$

To compare this to other noise sources, we can express this with an equivalent contrast ratio, C_r, by dividing the total read noise by the starlight core PSF count rate at the same location:

$$\begin{aligned} C_r &= \frac{\sigma_{r,M,R}}{M\tau n_\star} \\ &= \frac{\sqrt{MR\sigma_r^2}}{M\tau n_\star} \\ &= \sqrt{\frac{R}{M}}\frac{\sigma_r}{\tau n_\star}. \end{aligned}$$

We can again take similar values to that used in the Nemati spreadsheet. For UMa 47, a 5^{th} magnitude G1V star, his model used about $M = 100$ exposures of duration $\tau = 300$ s, and $R = 5$ pixels in the PSF core. The result, with $\sigma_r = 3$ e$^-$, is an overall read noise of $\sigma_{r,M,R} = 67$ e$^-$, and an equivalent read noise contrast of

$$\begin{aligned} C_r &= \sqrt{\frac{5}{100}} \quad \frac{3\ \mathrm{e}^-}{300\ \mathrm{s} \cdot 6.74 \times 10^6\ \mathrm{e}^-/\mathrm{s}} \\ &= 3.3 \times 10^{-10}. \end{aligned}$$

REFERENCES

Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231

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