

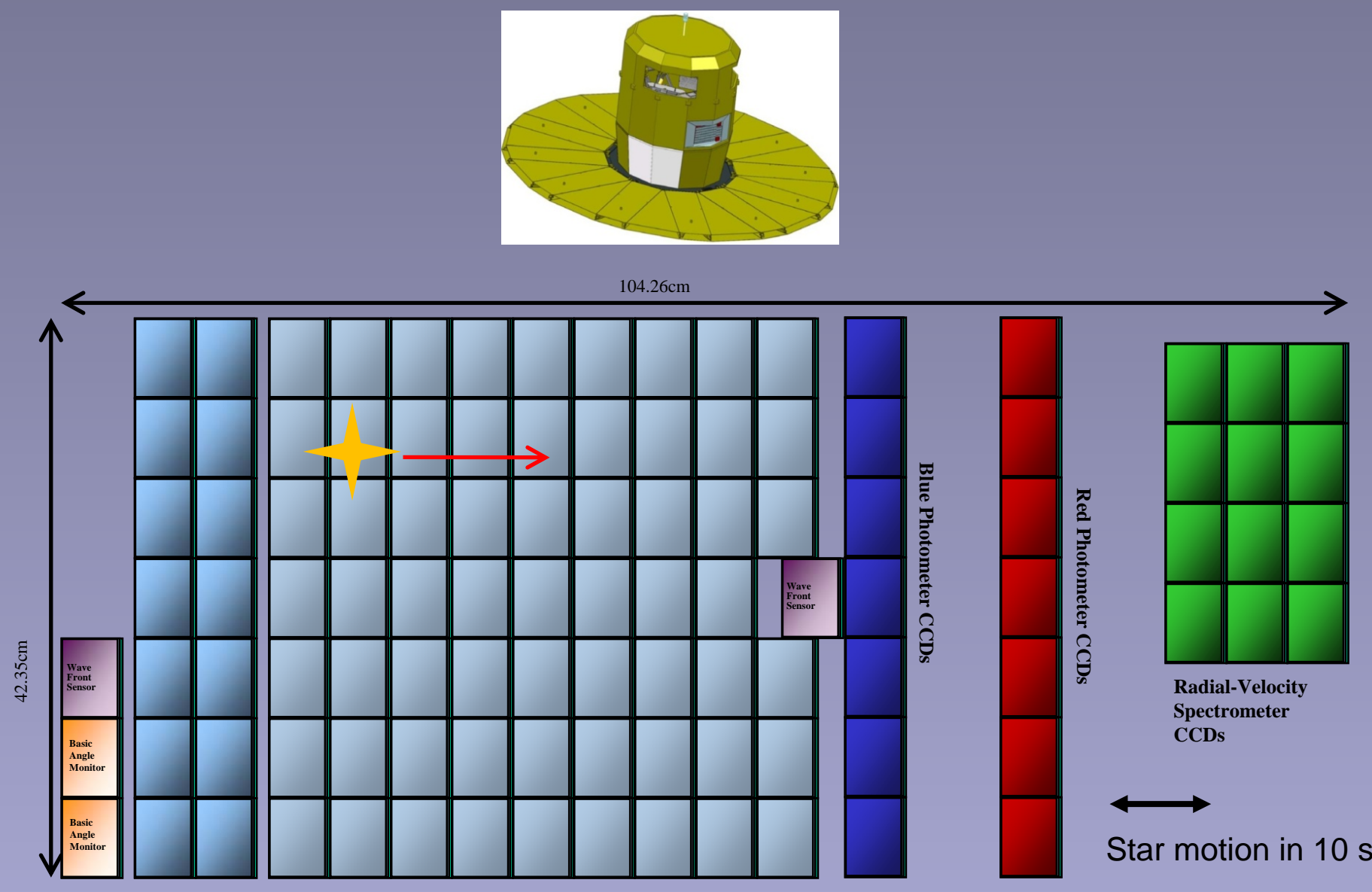
Simulating Charge Transfer Inefficiency Effects on Future Gaia Data

M. Weiler and C. Babusiaux

Observatoire de Paris – Meudon, GEPI, France

What is Gaia?

Gaia is an ESA cornerstone mission to perform high-accuracy astrometry as well as photometry of about 10^9 objects in the sky down to 20^{mag} . For the brightest objects also spectroscopic observations will be obtained. The Gaia spacecraft will scan the whole sky continuously during 5 years. Due to the scanning, astronomical sources will move over the focal plane equipped with an array of CCDs. The CCDs are operated in TDI (Time Delay and Integration) mode, shifting the charges produced by the light of the star with the same velocity towards the register as with which the star moves over the focal plane. Thus the integration time equals the transit time of a source over one CCD.



The primary goal of the Gaia mission is to do astrometry with a precision down to $10 \mu\text{arcsec}$ (at 10^{mag}).

To reach this goal, extreme accuracy in the determination of the center of a PSF is required. All effects that influence this quantity have to be evaluated and corrected for.

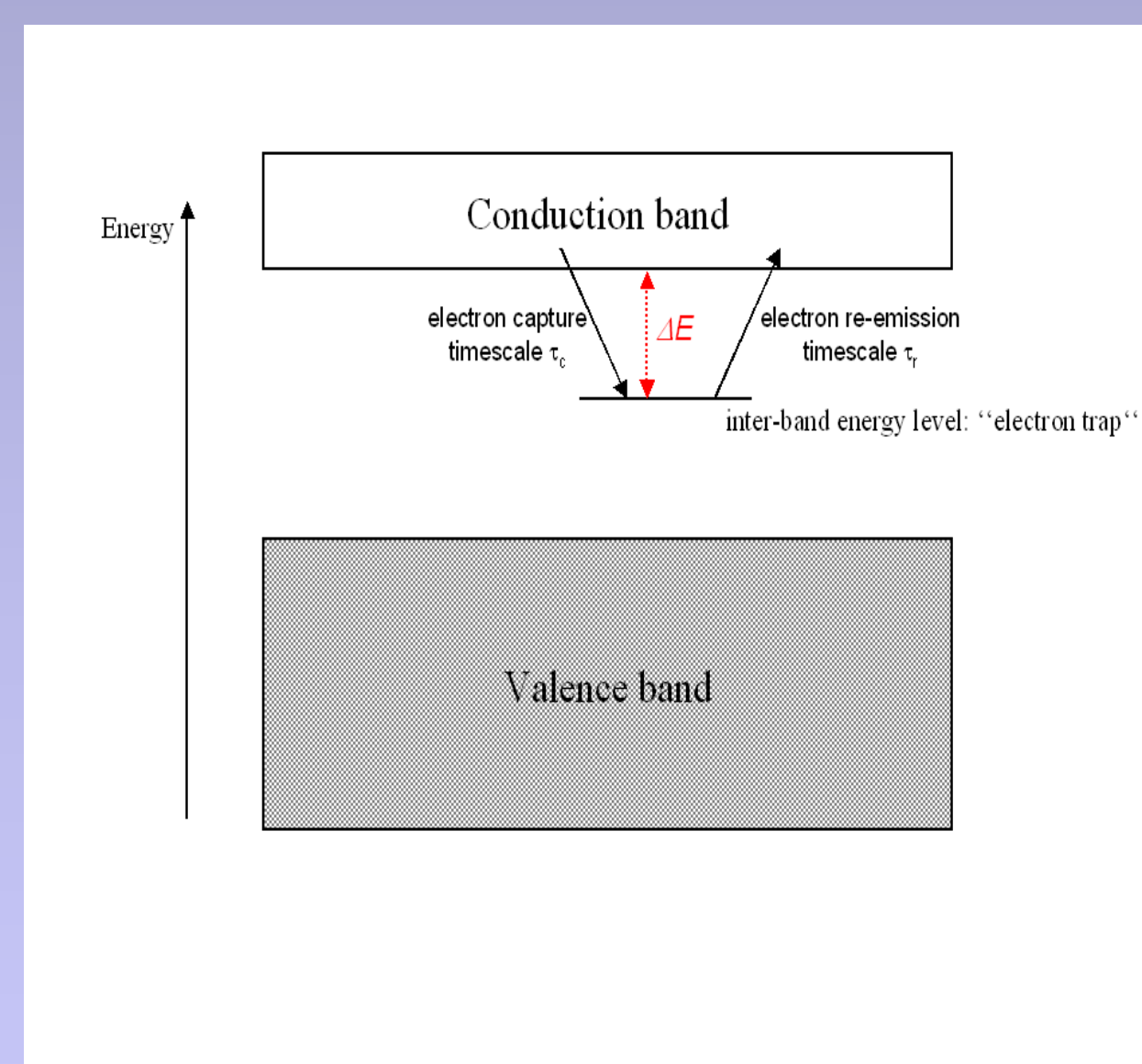
Figs. to the left: Gaia spacecraft and the lay-out of the focal plane. Each field corresponds to a 4500×1966 pixel CCD. Astronomical sources are transiting the focal plane from left to right. Courtesy: Alex Short

What is Charge Transfer Inefficiency?

When CCDs are subject to particle irradiation (e.g. protons at $\sim 10 \text{ MeV}$), the radiation causes (among other effects) vacancy defects in the semiconductor lattice by displacing atoms from their regular position within the lattice. Such vacancy defects introduce electronic energy levels between the valence band and the conduction band.

When transferring electrons in the conduction band through the CCD, some get in the inter-band energy levels. This capture of electrons occurs with a time scale $\tau_c = 1/(\sigma v_{\text{th}} n_e)$ (σ – capture cross section, v_{th} – thermal electron velocity, n_e – electron density), which is typically small ($\sim \mu\text{s}$).

From this energy level, electrons can be re-emitted to the conduction band with a time scale $\tau_r = 1/(\sigma v_{\text{th}} X_n N_c) e^{\Delta E/KT}$ (X_n – entropy factor, N_c – density of states in the conduction band)



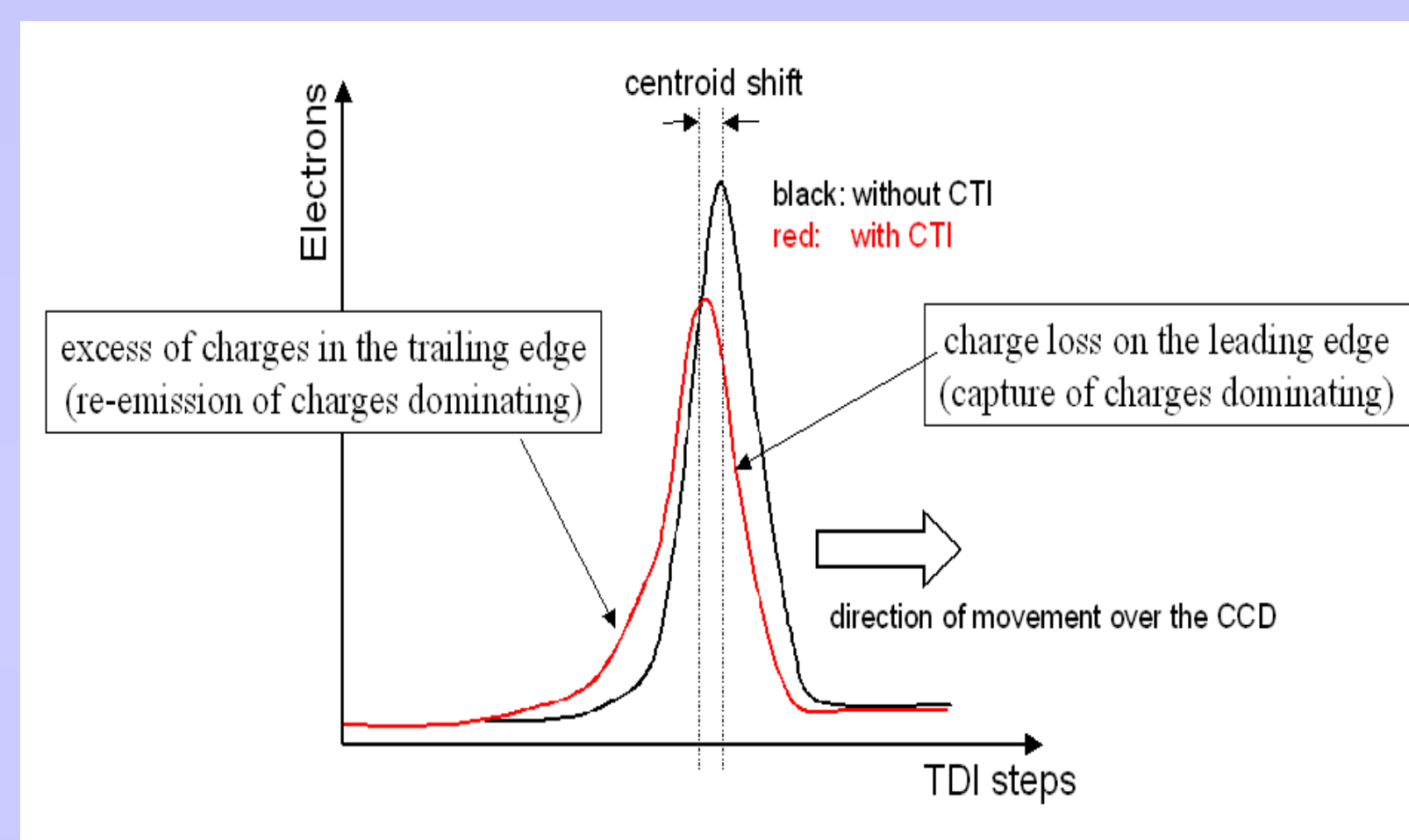
This time scale depend strongly on the CCD temperature and the position ΔE of the energy level with respect to the lower end of the conduction band. They typically range from $\sim \mu\text{s}$ up to $\sim 10^2 \text{ s}$. Because of the long time electrons can remain in the inter-band energy level, they are said to be trapped in an electron trap.

Electrons in a trap are temporary removed from the charge transfer in the conduction band. Thus the presence of traps reduces the charge transfer efficiency. This effect is therefore called Charge Transfer Inefficiency (CTI).

What are the effects of CTI on Gaia observations?

The capture and re-emission of electrons causes a deformation of the point-spread functions:

- Loss of electrons in the leading edge of a PSF and additional electrons in the trailing edge. As a result, a shift in the center of the PSF is expected. This affects the astrometric accuracy.
- Within a certain small window around the center of the PSF, electrons are lost due to CTI. This affects the photometry.
- The shape of spectral lines are altered. This affects spectrometry.



Since the electron release time constants can be very long (up to 10^2 s), traps can remain filled and thus blocked for electrons resulting from another star following the star that has filled traps.

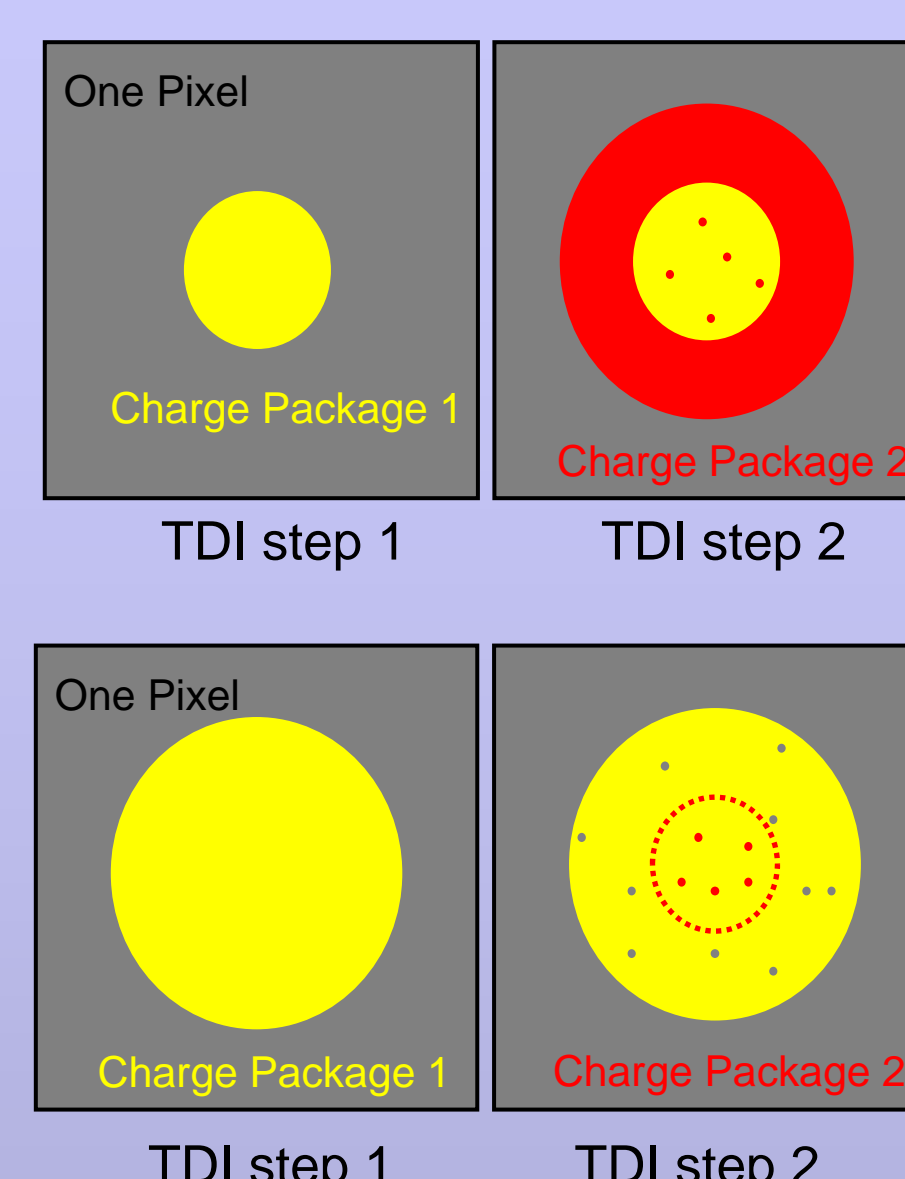
Furthermore, released electrons can be added to the PSF of a following star after beeing captured by a preceding star.

This introduces a dependency of the CTI effects upon one star on the transit history of the CCD (i.e. the sequence of stars observed before).

How are the CTI effects modelled?

The model employed here makes several simplifying assumptions:

- Electrons are trapped immediately when approaching a trap ($\tau_c \ll \text{TDI period}$)
- Release of electrons according to a sum of five exponentials (five traps species): $R(k) = \sum_j A_j e^{-\mu_j k}$ ($R(k)$ – electron release probability after k TDI periods, A_j – relative abundance of trap species j , μ_j – inverse time release constant of species j)
- A volume-based approach is used to describe the numbers of traps encountered by a certain number of electrons in one CCD pixel
- The Gaia data simulator GIBIS (Gaia Instrument and Basic Image Simulator, Babusiaux 2006) is used to simulate the Gaia observations

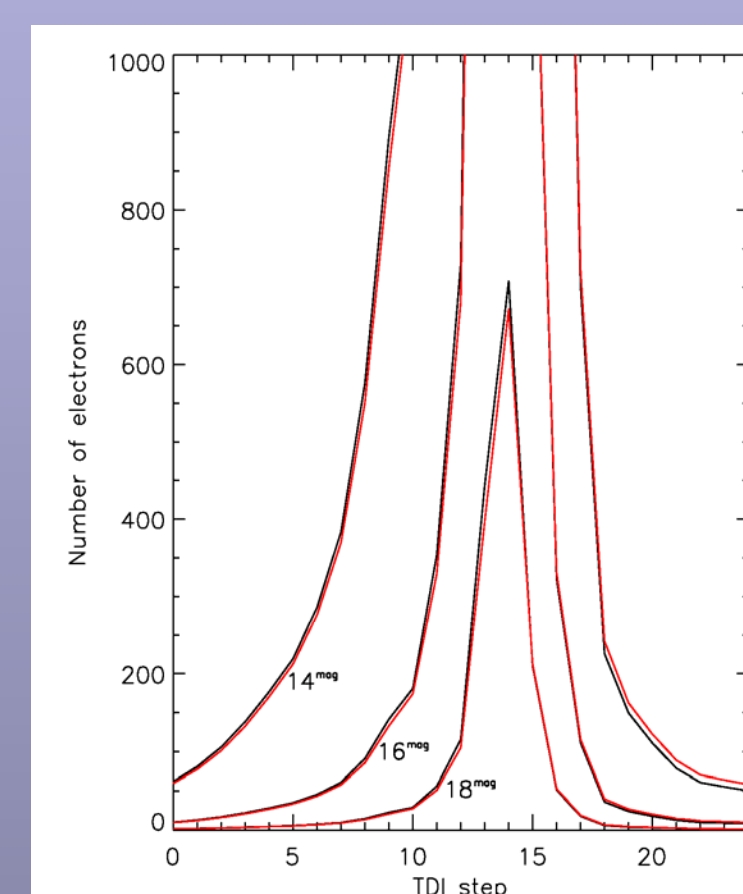


A volume-based model makes the assumption that an electron package in a CCD pixel can access a certain volume and fills all traps inside this volume. Traps outside the volume cannot be filled by the charge package.

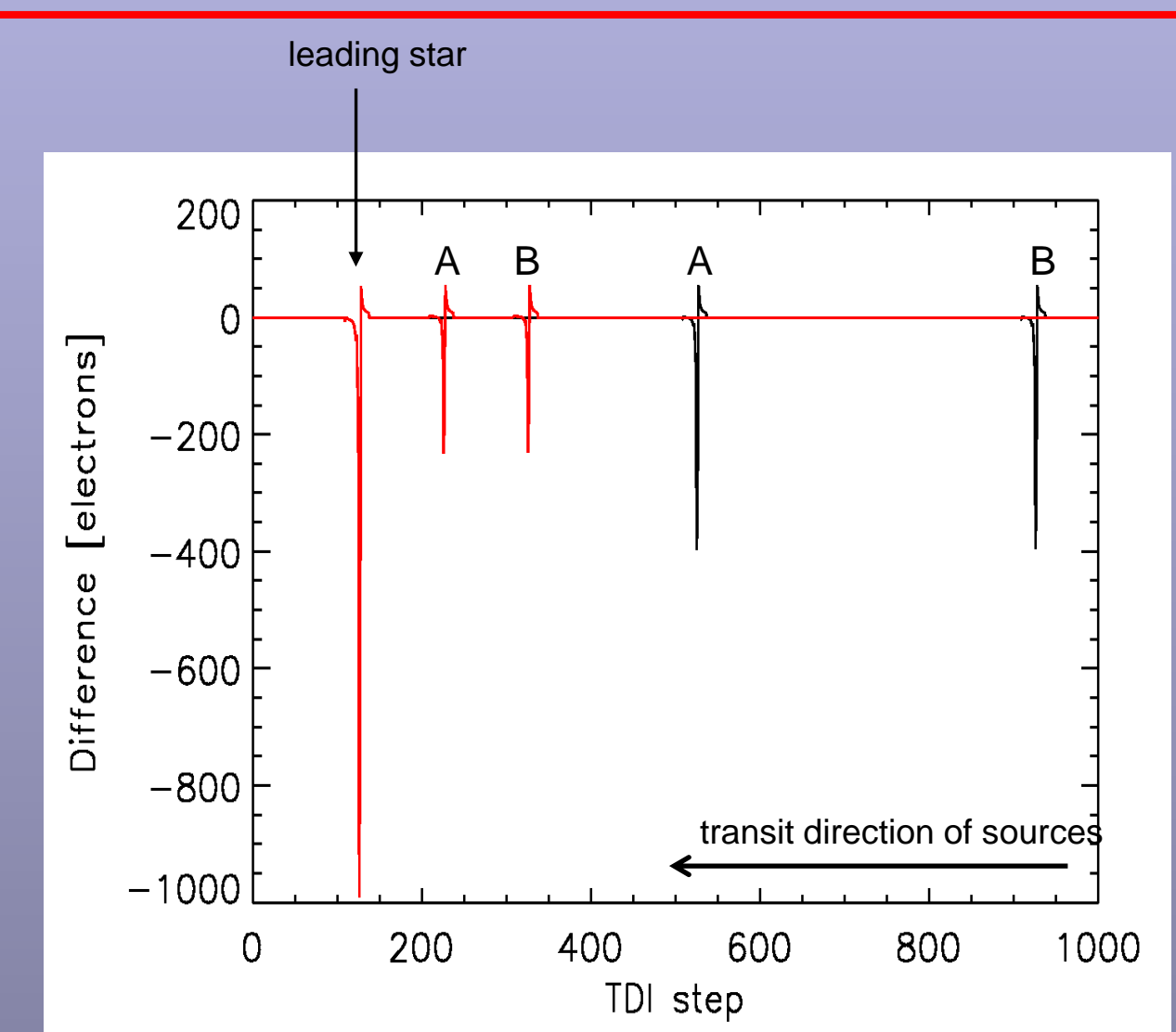
This is illustrated in the Fig. to the left. Upper panel: A smaller charge package (yellow) enters a pixel in one TDI step. In the next step a larger package (red) is entering the pixel where the yellow package has been in the step before. The larger package can only fill the traps within the volume occupied by the yellow package before that are empty again after one TDI period, as well as all traps in the outer red volume unreachable for the smaller charge package. Lower panel: The first charge package (yellow) is larger than the second package (red). The second package can only fill traps that are empty again after one TDI period inside the dashed circle. Charge loss in the second package is strongly reduced in this case.

Simulation Results

The image to the right shows a cut through the central part of the PSF of stars of three different magnitudes. Black lines show the PSF without CTI effects, red curves with CTI effects. The typical behaviour can be seen: charge loss at the leading edge and excess charges at the trailing edge. The stars are moving from right to left over the focal plane.

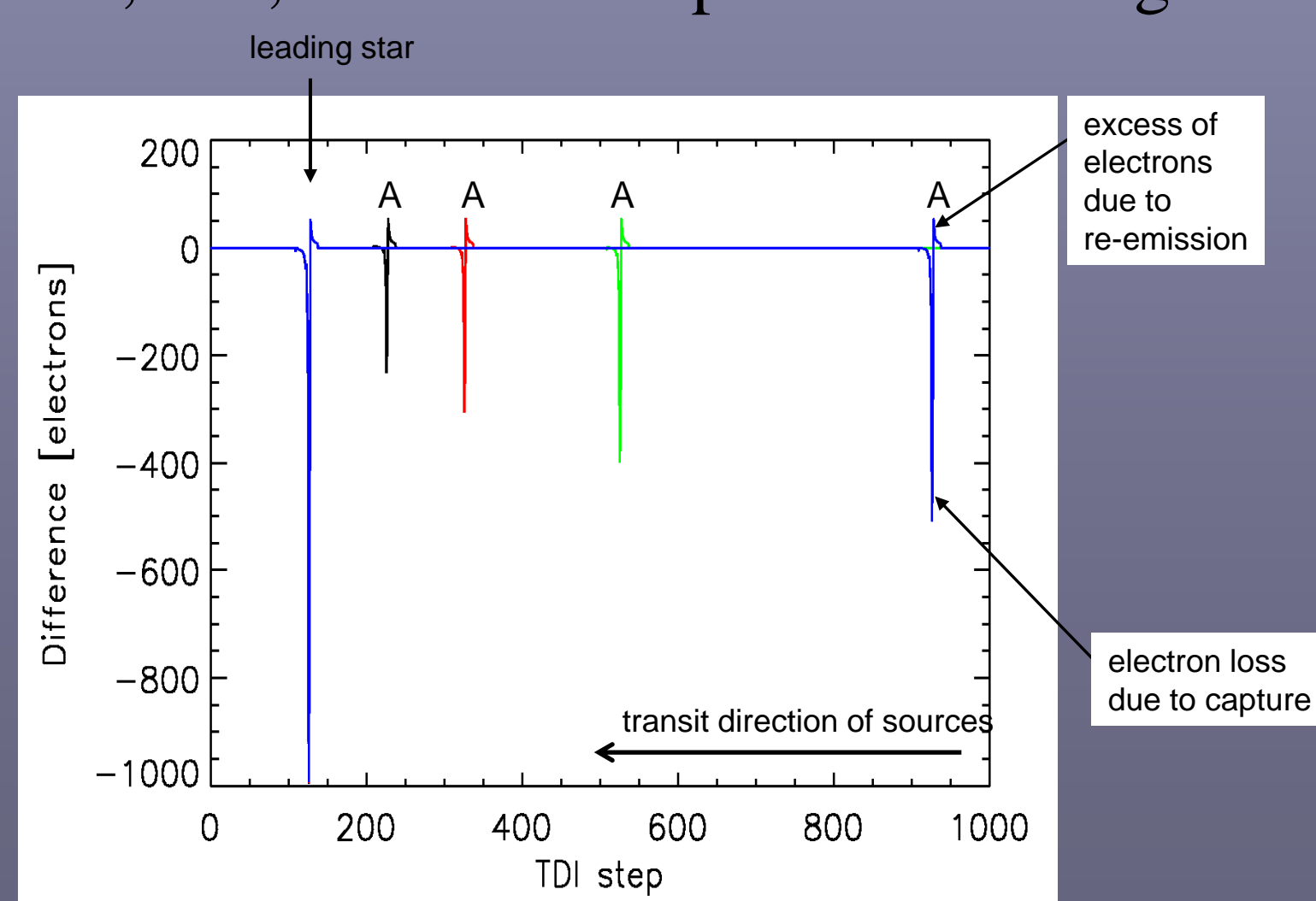


The case of two stars (A and B) following one star in distances of 100 and 200, and 400 and 800 TDI periods is shown in the Fig. to the right. For the first trailing star (A), the CTI effects are again reduced. For the second trailing star (B), no further reduction can be seen. This is the case since all stars have the same brightness. So star A refills the traps that have released charges from the leading star. It thus restores the same situation that itself has approached before.



Dependency of CTI effects on the distance between two sources:

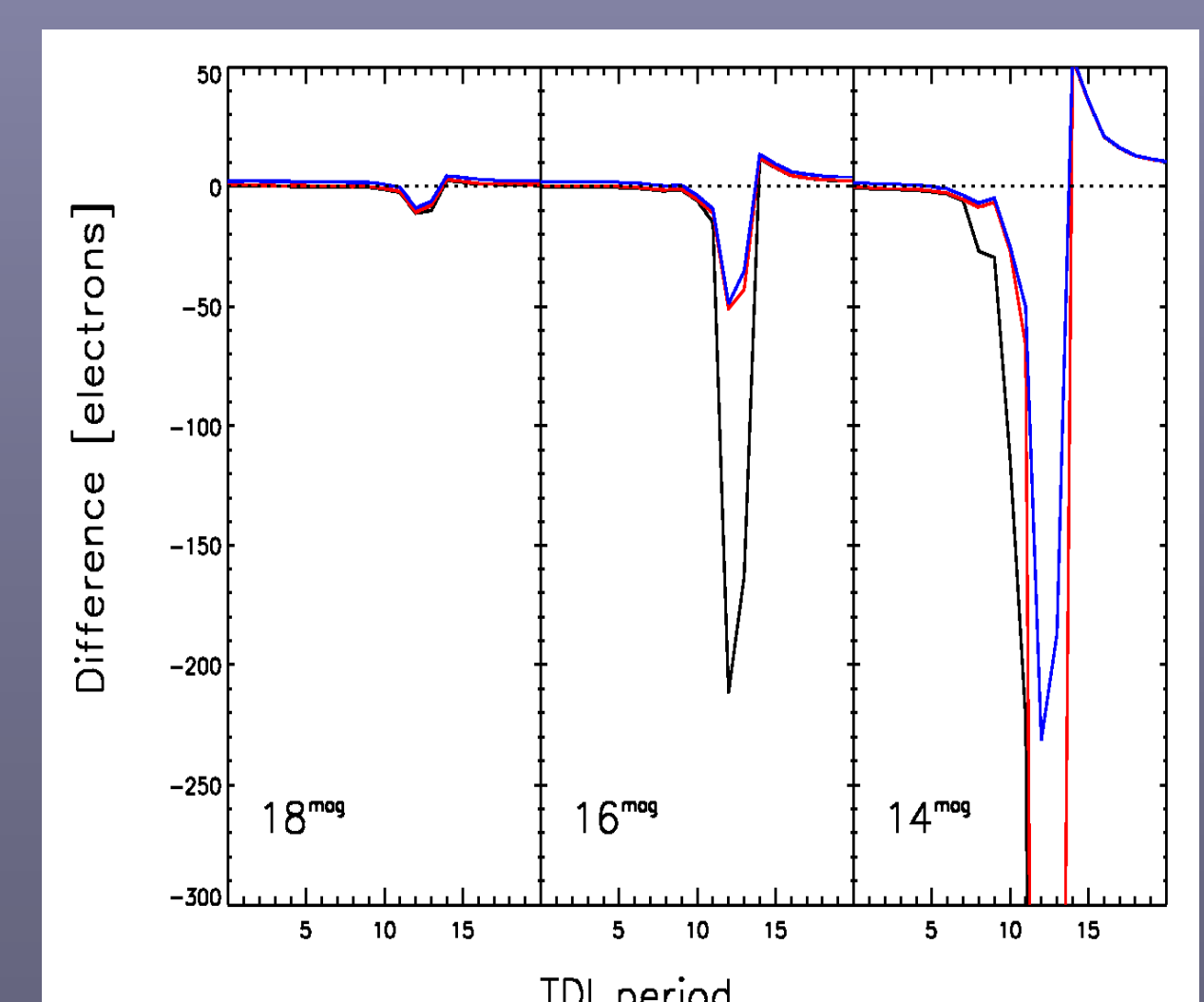
Simulations for two stars of the same brightness (14^{mag}) at different separations: 100, 200, 400, and 800 TDI periods. The Fig. below shows the difference in electrons between the PSF with CTI effects and without, for the center column. Negative values mean loss of electrons due to charge capture, positive values an excess in electrons due to charge re-emission. For the leading star (left), the effect of CTI is strongest, for the following star (A) the CTI effects are reduced. The reduction decreases with increasing separation of the stars.



between the PSF with CTI effects and without, for the center column. Negative values mean loss of electrons due to charge capture, positive values an excess in electrons due to charge re-emission. For the leading star (left), the effect of CTI is strongest, for the following star (A) the CTI effects are reduced. The reduction decreases with increasing separation of the stars.

Dependency of the CTI effects on the magnitude of the stars:

The results of a computation for two stars in a fixed distance (100 TDI periods) is shown to the right. The Fig. shows the difference in electrons for the trailing star of 18^{mag} , 16^{mag} , and 14^{mag} , while the leading star was 18^{mag} (back), 16^{mag} (red), and 14^{mag} (blue). For the faintest star, a slight excess in electrons can be observed if preceded by a bright star (due to re-emission of electrons captured from the bright star). For the other stars, a strong reduction of the CTI effects can only be seen if the preceding star is of similar brightness or brighter than the trailing star.



Warning: The computations were performed with preliminary values for the number of traps and time release constants. Before final conclusions can be drawn, these parameters have to be further constrained.