The Extinction Curve of AA Tau's 2011 Dimming Event:

Using Line Veiling to Untangle Inner Disk Emission from Dimming Due to Dust

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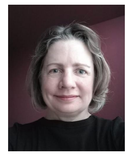

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Introduction: 2011 Fading Event

- AA Tau: moderately accreting Classical T Tauri Star (CTTS) viewed at disk high inclination (i ~ 75°; Basri & Bertout 1989)
- Multi-decadal (1985-2010) photometric monitoring confirms persistent quasi-periodic (p = 8.2 days) variations with 0.1-0.5 mag amplitude (Grankin+ 2007, Percy+ 2010); spectroscopic & polarization measurements consistent with stellar occultations by warped inner disk (Bouvier+ 1999, 2007)
- Deep (>2 mag), persistent (3+ year) fading event began in mid-late 2011 (see Figure 1); interpreted as by Bouvier+ 2013 as enhanced extinction by the inner circumstellar disk (see Figure 2)

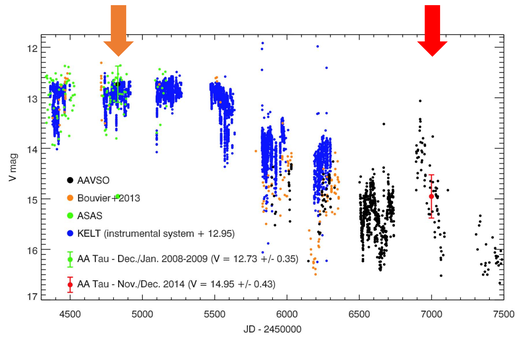

Fig. 1 – Multi-year V-band light curve for AA Tau, constructed with data obtained by the All-Sky Automated Survey (Pojmanski+ 2002), Mt. Maindanak long term monitoring program (Grankin+ 2007, as reported by Bouvier+ 2013) and AAVSO observers. Orange and red arrows at the top of the panel show the timing of our 2008 and 2014 spectroscopic observations: mean V-band magnitudes for these periods demonstrate the 2+ magnitude fading event from V = 12.7 to V = 14.9 that occurred in 2011.

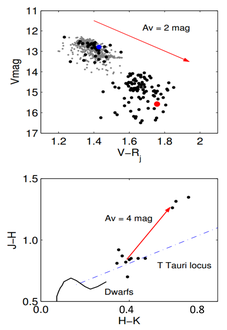

Fig. 2 – *(reproduced from Bouvier+ 2013)* AA Tau's location in V vs. V-R color-magnitude and J-H vs. H-K color-color space before and after the 2011 fading event. Each panel includes a red arrow showing extinction vectors computed by Bouvier+ 2013, who conclude that the enhanced extinction is more likely.

Spectra: Before and After the Fading Event

- Near-simultaneous (Δt < 2 hours) optical (Palomar/DoubleSpec; Herczeg & Hillenbrand 2014) and near-infrared (NIR; APO/TripleSpec) spectra obtained in Dec. 2008 (pre-fade) (see Figure 3, orange line)
- Following 2011 fade, we obtained a second set of near-simultaneous optical (UH-88/SNIFS) and NIR (APO/TripleSpec) spectra (see Figure 3, red line) to enable direct measurement of wavelength dependence of 2011 fading event

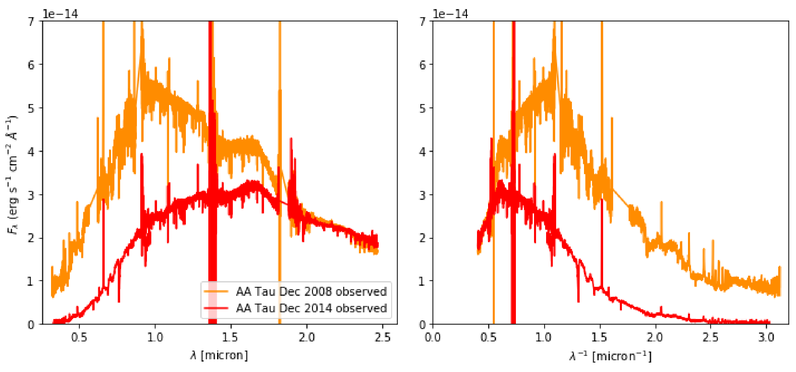

Fig. 3 – AA Tau spectra before (orange) and after (red) the dimming event, allowing direct calculation of the wavelength-dependent extinction curve of the event. Left panel shows flux versus wavelength, more familiar to stellar astronomers, while the right panel shows flux versus inverse wavelength, more familiar to interstellar medium astronomers. Note the slight brightening of AA Tau at 2.5 microns; see next panels for explanation.

References

Basri & Bertout 1989
Bouvier et al. 1999
Bouvier et al. 2007
Bouvier et al. 2013
Cardelli et al. 1989
Fischer et al. 2011
Fitzpatrick 2004
Fitzpatrick & Massa 1999
Gordon et al. 2016
Grankin et al. 2007
Herczeg & Hillenbrand 2014
Lim et al. 2016
Maiz Apellaniz et al 2014
Percy 2010
Pojmanski et al. 2002

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Problem? A_V = 2 in visible, A_V = 4 in NIR

- Our direct calculation of the flux ratio before and after the dimming event implies an extinction curve that is almost consistent with an A_V = 2 mag extinction law, not A_V = 4 mag from NIR color-color diagram (see Figure 4)
- Normalization to the K-band and synthetic photometry show that the anomalous NIR color-color diagram is caused by the steep slope of the extinction curve at >2 microns (see Figure 5)
- Larger overall amount of extinction reproduces the slope of the NIR extinction curve, but does not reproduce the amount of extinction in any passbands

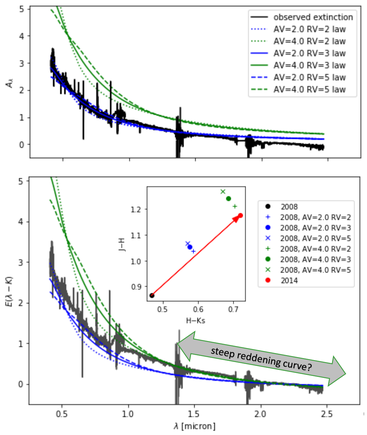

Fig. 4 – AA Tau extinction event curve naively inferred from the before-to-after flux ratio. Fitzpatrick & Massa 1999 extinction laws with various values of R_V are shown for A_V = 2 (blue) and A_V = 4 (green), the two values of visual extinction implied by Figure 2.

Fig. 5 – AA Tau color-excess curve naively inferred from the before-to-after flux ratio and synthetic photometry. No part of the extinction curve seems consistent with any of the A_V = 4 (green) curves, so why does the NIR color-color diagram (Figure 2, and inset) imply the large extinction? The long vector in a color-color diagram means a steep extinction curve. The only way to reproduce steep NIR extinction with FM99 curve is a large overall scaling A_V.

Solved! A_V = 2, but unusually steep NIR extinction

Problem? Anomalous NIR extinction curve

- NIR extinction curve is too steep: no commonly-used extinction curve can reproduce the K-band extinction curve shape; "negative extinction" at 2.5 microns implies emission
- Line veiling by inner-disk emission allows us to measure emission through equivalent width ratio, as well as extinction separately through the integrated line intensity ratios

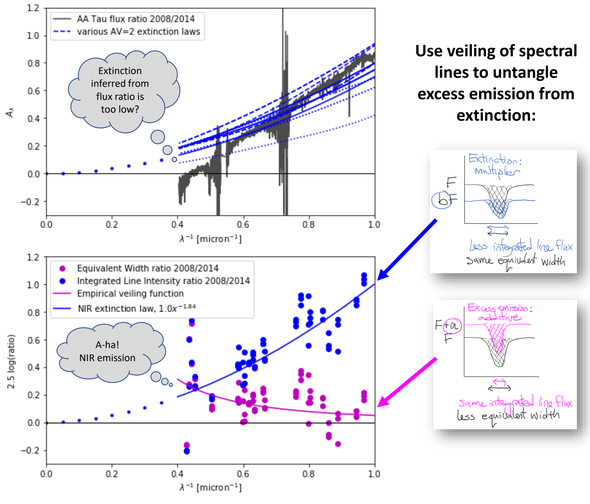

Fig. 6 – Flux ratios for the AA Tau event. The top panel shows that the steep flux ratio (extinction, naively) is not reproduced by any of the extinction laws in the **dust_extinction** affiliated package of Astropy. Unphysically low extinction at the K band implies emission. Measuring line equivalent widths allow us to measure excess continuum emission through veiling; see Fischer et al. 2011. Integrated line intensities are independent of continuum emission, and therefore can be used to measure the remaining extinction in the spectral flux ratios. Bottom panel shows confirmation that the extinction has an unsurprising shape, consistent with well-known extinction curves.

Solved! Excess NIR emission found in line veiling

Before-to-After Ratio: Extinction Curve & Color Excesses

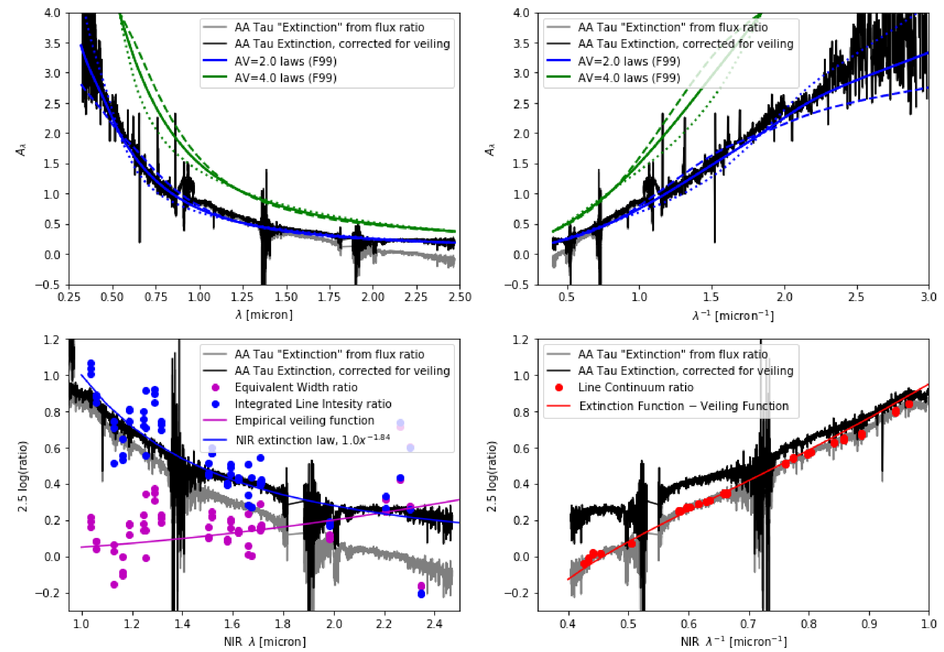

Fig. 7 – Extinction curve of the AA Tau dimming event. Top panels show that, when corrected for excess continuum emission in the NIR, the extinction curve is consistent with a standard extinction law. Left bottom panel shows that the ratio of the integrated line intensities (blue) in log space do indeed trace the extinction curve. Right bottom panel shows a sanity check: the ratio of the chi-by-eye functions describing the integrated line intensities (blue) and equivalent width intensities (magenta) do reproduce the continuum flux of the original flux ratio that includes both increased extinction and increased NIR emission (red).

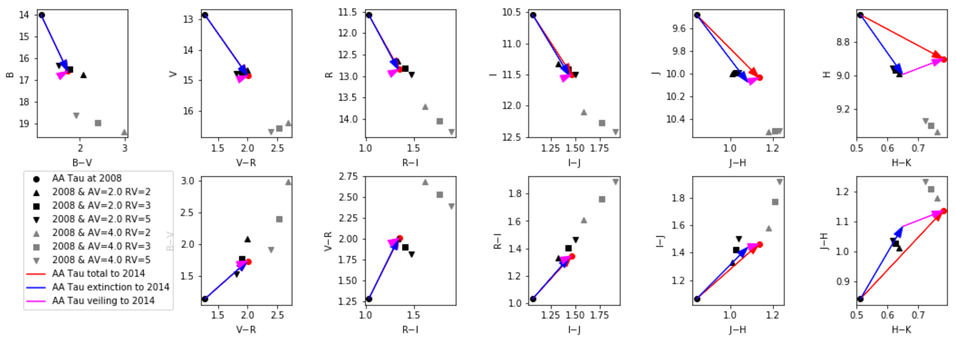

Fig. 8 – Synthetic photometry color-magnitude and color-color diagrams of before (black circle) and after (red circle) the AA Tau dimming event. Black symbols show how AA Tau would have dimmed due to standard extinction laws with A_V = 2 mag (black) and A_V = 4 mag (grey). Extinction/reddening vectors are shown for the excess NIR emission measured via veiling (magenta) and the actual extinction due to foreground dust (blue). Note that the blue and magenta vectors add to equal the net extinction/reddening vectors in red. After correction, the AA Tau dimming event is entirely consistent with standard A_V = 2 mag extinction.

Conclusions: Measuring Extinction of T Tauri Stars

This work shows that when measuring the local extinction of T Tauri stars, obtaining spectra is critically important. First, photometric color-color diagrams measure the shape of the extinction curve, the differential extinction between bands, not necessarily the total amount of extinction. Spectra allow the shape and amount of extinction to be measured independently. Second, excess NIR emission can be confused with anomalously low or steeply decreasing extinction. Spectral lines allow the emission to be measured by the equivalent width ratios, and extinction by the integrated line intensity ratios. We will explore this technique further in an upcoming paper.

Applying these techniques, we find that the AA Tau dimming event of 2011 is consistent with increased extinction of A_V = 2 mag and standard wavelength dependence from the optical through the NIR, plus excess NIR emission presumably from the inner disk.

We thank Western Washington University and the Research Corporation for support that facilitated this work and its presentation. This research made use of Astropy, a community-developed core Python package for astronomy (www.astropy.org), as well as two Astropy-affiliated packages, **dust_extinction** (github.com/karllark/dust_extinction) developed by Karl Gordon with contribution from Kristen Larson, and **synphot** (synphot.readthedocs.io) developed by Pey Lian Lim and STScI.